International Colloquium on Large Wind-Power Plants: Interaction, Control, and Integration

Book of Abstracts

Edited by Johan Meyers, Charles Meneveau, Ben Hobbs

Wednesday 8 July 2015

08.45-09.00h	**Welcome**	
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	11.30h	Full scale wake experiments at Horns Rev – The case of downregulation [p. 18] *Gregor Giebel, Tuhfe Göcmen Bozkurt, Mads Rajczyk Skjelmose, Jesper Runge Kristoffersen*
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	16.30h	Optimal coordinated control of energy extraction in wind farms [p. 25] *Johan Meyers, Jay P. Goit, Wim Munters*
	16.50h	Practical tools for optimisation of wind plant sector management strategies [p. 26] *Ervin Bossanyi, Tiago Jorge*
	17.10h	Wind farm power optimization and control in highly variable multiple wake flows [p. 27] *Marcus Therkildsen, Jürgen Herp, Martin Greiner*
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	17.50h	Improved onshore AC grid frequency & DC grid voltage control from offshore wind power plants connected through HVDC using wind speed forecast [p. 29] *Jayachandra N. Sakamuri, Pieter Tielens, Dirk Van Hertem, Nicolaos A. Cutululis*
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	14.50h	On the influence of Coriolis forces on the structure and evolution of wind-turbine wakes [p. 36] *Mahdi Abkar, Fernando Porté-Agel*
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	17.00h	The simulation of wind farm wakes with mesoscale models [p. 41] *P. J. H. Volker, J. Bagder, A. N. Hahmann, M. Badger, C. B. Hasager*
	17.20h	Impact of wind farms on the North Sea climate [p. 42] *Fabien Chatterjee, Dries Allaerts, Nicole Van Lipzig, Ulrich Blahak, Johan Meyers*
	17.40h	An LES study of a large wind farm during a realistic (CASES99) diurnal cycle [p. 43] *Varun Sharma, Marc Calaf, Marc B. Parlange, Michael Lehning*
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	18.20h	Structural Impact of Different Low Level Jet Types over Wind Turbines in West Texas [p. 45] *Walter Gutierrez, Guillermo Araya, Praju Kiliyanpilakkil, Arquimedes Ruiz-Columbie, Murat Tutkun, Luciano Castillo*
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	09.50h	Dynamic mode decomposition applied to large-eddy simulations of wind farms [p. 47] *Vaughan Thomas, Claire VerHulst, Charles Meneveau, Dennice Gayme*
	10.10h	Data-driven reduced order model for prediction of wind turbine wakes [p. 48] *Giacomo Valerio Iungo, Christian Santoni, Stefano Leonardi*
	10.30h	Statistical modeling of wind farm power production: a study of predictive accuracy for multiple wind farms [p. 49] *Andrea Staid, Claire VerHulst, Seth D. Guikema*
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	12.30h	Turbulence analysis upstream of a wind turbine: a LES approach to improve wind LIDAR technology [p. 54] *Gerard Cortina, Varun Sharma, Marc Calaf*
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	14.20h	Wind Turbine Box, the flow around a characteristic wind turbine [p. 56] *Marc Calaf, Gerard Cortina, Yohhan Dinkar, Varun Sharma*
	14.40h	Comparison of an actuator line model implementation in three different large-eddy simulation codes [p. 57] *Luis A. Martínez, Ali Emre Yilmaz, Matthew J. Churchfield, Johan Meyers, Charles Meneveau*
	15.00h	Comparison of wind turbine wake properties using actuator line and disc approaches [p. 58] *Sasan Sarmast, Stefan Ivanell*
15.20h	**Closure**	

Keynote Abstracts

What the characteristics of wind power mean for integration into power grids

JAY APT [1]

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Key words: Wind farms, Integration, Reserves, Variability

Increasing the market share of variable renewable electric power generation in the United States from the present 4% is eminently feasible [1]. The variability of wind and solar power is much less at high frequencies than at low frequencies, so that slow-ramping generators can compensate for most of the variability [2]. The inter-annual variability of wind power is beginning to be understood [3, 4], as are the biases in its day-ahead forecasts [5]. Geographic aggregation of wind and solar power has been proposed as a method to smooth their variability; for wind power it has been shown that there is little smoothing at times scales where the magnitude of variability is strongest and the point of diminishing returns is reached after a relatively few wind plants have been interconnected [3, 6]. It is now possible to predict the amount of additional capacity of dispatchable generation that must be procured by system operators to cover the uncertainty in wind forecasts [7]. There are a number of assumptions made in many large-scale grid integration studies that can be improved, leading to better integration planning [8].

[1] J. Apt and P. Jaramillo, *Variable Renewable Energy and the Electricity Grid* (Routledge, RFF Press, 2014).

[2] J. Apt, "The Spectrum of Power from Wind Turbines," Journal of Power Sources **169** (2007).

[3] W. Katzenstein, E. Fertig, and J. Apt, "The Variability of Interconnected Wind Plants," Energy Policy **38** (2010).

[4] S. Rose and J. Apt, "What Can Reanalysis Data Tell Us About Wind Power?," Renewable Energy (in press).

[5] B. Mauch, J. Apt, P.M.S. Carvalho, and M. Small, "An Effective Method for Modeling Wind Power Forecast Uncertainty," Energy Systems **4** (2013).

[6] E. Fertig, P. Jaramillo, and J. Apt, "The Effect of Long-Distance Interconnection on Wind Power Variability," Environmental Research Letters **7** (2012).

[7] B. Mauch, J, Apt, P.M.S. Carvalho, and P. Jaramillo, "What Day-Ahead Reserves are Need in Electric Grids with High Levels of Wind Power?," Environmental Research Letters **8** (2013).

[8] J. Dowds, P. Hines, T. Ryan, W. Buchanan, E. Kirby, J. Apt, and P. Jaramillo, "A Review of Large-Scale Wind Integration Studies," Renewable & Sustainable Energy Reviews **49** (2015).

Lidar measurements in the atmospheric boundary layer and around wind turbines

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Key words: Doppler lidar measurements, wakes, flow over complex terrain

Only ten years ago Doppler lidars, which measure remotely the winds in the atmosphere, had barely been introduced in the field of wind energy research, but right from the start the potential for their use was clear.

The first challenge was to ensure that the instruments actually measured the wind speed with the high precision needed for wind resource estimation and power curve validation (Smith et al. 2006). Academia and industry collaboration ensured rapid reduction of the errors of lidar wind measurement.

Later Bingöl et al. (2010) showed how a scanning lidar could be used to validate models of wake meandering, and many more lidar assisted experiments on wake flow has been carried out during the last five years. Most recently, various groups are investigating wind turbine wakes over complex terrain and also multiple wakes.

Another challenge is the measurement of turbulence, which is important in connection with dynamic load estimation on wind turbines. Standard profiling lidars suffer, apart from availability, from two basic shortcomings; a long measuring volume and that different components of the wind vector are measured in different points in the atmosphere (Mann et al. 2010). These will modify the turbulence levels in comparison with a point measurement such as a ultrasonic anemometer. Sathe and Mann (2013) reviewed those challenges and suggested to change the scanning methodology and treatment of the data to improve the similarity between point measurement and lidar measurements (Sathe et al. 2015),

Scanning lidars has been used to scan the flow over terrain in very different way. Krishnamurthy et al. (2013) scanned the flow over tens of square kilometers of complex terrain using a single instrument, but current and future campaigns will deploy many synchronized instruments, as done in a pilot study at Perdigao in Portugal. A very rapidly scanning Doppler lidar measured the wake after the escarpment at Bolund acquiring wind profiles, which have been difficult to reproduce in computer models or wind tunnel tests (Mann et al. 2014).

Lidar assisted wind turbine control must be cheap and reliable. There is potential for better yaw correction and reduced loads in combination with pitch control, but the real potential is still uncertain Bossanyi et al. (2012).

In summary, Doppler lidars for wind energy applications is a rapidly growing and very interesting field.

References

Bingöl, F., Mann, J. and Larsen, G. C.: 2010, Lidar measurements of wake dynamics part I: One dimensional scanning, *Wind Energy* **13**(1), 51–61.

Bossanyi, E., Savini, B., Iribas, M., Hau, M., Fischer, B., Schlipf, D., Engelen, T., Rossetti, M. and Carcangiu, C.: 2012, Advanced controller research for multi-mw wind turbines in the upwind project, *Wind Energy* **15**(1), 119–145.

Krishnamurthy, R., Choukulkar, A., Calhoun, R., Fine, J., Oliver, A. and Barr, K.: 2013, Coherent doppler lidar for wind farm characterization, *Wind Energy* **16**(2), 189–206.

Mann, J., Angelou, N., Sjöholm, M., Mikkelsen, T., Hansen, K. H., Cavar, D. and Berg, J.: 2014, Laser scanning of a recirculation zone on the Bolund escarpment, *J. Phys: Conf. Ser.* **555**, 012066.

Mann, J., Peña, A., Bingöl, F., Wagner, R. and Courtney, M. S.: 2010, Lidar scanning of momentum flux in and above the surface layer, *J. Atmos. Ocean. Technol.* **27**(6), 959–976.

Sathe, A. and Mann, J.: 2013, A review of turbulence measurements using ground-based wind lidars., *Atmospheric Measurement Techniques* **6**(11), 3147–3167.

Sathe, A., Mann, J., Vasiljevic, N. and Lea, G.: 2015, A six-beam method to measure turbulence statistics using ground-based wind lidars, *Atmospheric Measurement Techniques* **8**, 729–740.

Smith, D. A., Harris, M., Coffey, A. S., Mikkelsen, T., Jørgensen, H. E., Mann, J. and Danielian, R.: 2006, Wind lidar evaluation at the Danish wind test site Høvsøre, *Wind Energy* **9**(1–2), 87–93.

Wind Farm Control: Strategies and Testing

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Key words: Wind farms, Control, Wind tunnel testing

In the past, most of the research in wind energy technology focused on the optimization of wind turbines. In recent years, interest has expanded from the level of the individual machines to the one of wind farms. Optimal site selection, layout and control of wind farms are extremely challenging tasks that require an understanding of the aerodynamic interactions among the various machines and with the environment. These are all problems that are not yet fully understood and that are still challenging to model in an accurate way.

Figure 1: at left, wake and turbulence effects in a wind farm; at right: power curtailment and wake deflection strategies for wind farm cooperative control.

In this contribution, we describe our ongoing work on wind farm control. Ad hoc observers are used for detecting wake interaction conditions, in turn enabling cooperative control strategies for power maximization and load mitigation by power curtailment and active wake deflection. Our research program includes a scaled experimental facility for the simulation of wind farms in a boundary layer wind tunnel, which is used for the validation of simulation tools and the verification of control strategies.

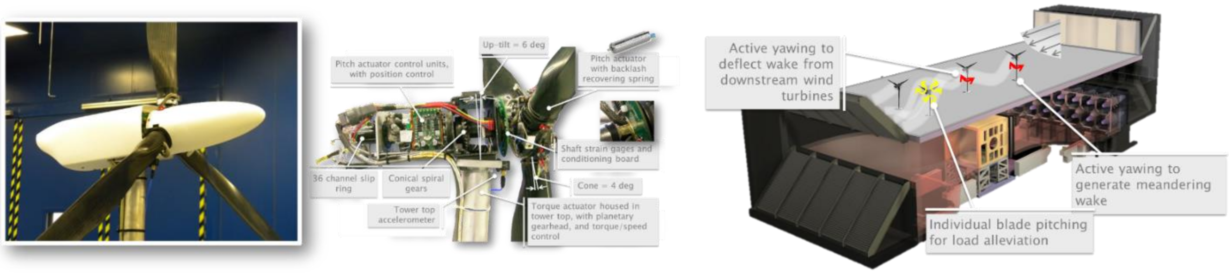

Figure 2: at left, scaled wind turbine models; at right: experimental setup in the wind tunnel for the testing of wind farm control strategies.

"Wind, solar and natural gas: issues for high wind energy penetration in electric power grids"

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Key words: Electric power grids, wind energy, natural gas, control performance, investment planning, co-optimization

In each year since 2005, additional electric generation installed in the US has been dominated by wind and natural gas-fired capacity; since 2012, solar-PV has begun to have significant presence [1]. Indications are that these three resource types will continue to dominate capacity additions for at least the next 10 years [2]. The increasing penetrations of wind and solar-PV drive the need for increased response flexibility from the remaining resources, something that the natural gas-fired units are capable of providing. However, despite near-term benefits of natural gas, there are significant long-term risks to increasing dependence on it, including greenhouse gas production and eventual price volatility. In this talk, we address first the need for real-time adjustment of regulation reserve requirements in order to preserve frequency control performance under high variable energy resources. Then we illustrate the need for embedding reserve-related operational constraints, driven by increased net load variability, within expansion planning models. We then show use of these models to co-optimize investments in natural gas pipelines, generation resources, and electric transmission, illustrating their use on the U.S. Eastern interconnected power grid. We conclude the talk by comparing benefits and risks associated with futures wherein each one of these three energy resources is dominant.

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[1] U.S. Department of Energy, "Wind Vision: A New Era for Wind Power in the United States," March, 2015.

[2] National Electric Reliability Corporation, "2014 Long-Term Reliability Assessment," November, 2014.

Management of energy resources for flexible and efficient power systems

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Key words: Power Networks, Energy Storage, Renewable Energy Integration

The growth of wind energy is one of many factors driving rapid changes to the power system. This large-scale renewable energy integration coupled with demand growth and new demand-side technologies are changing the long held paradigms of scheduling dispatchable generation resources to track predictable demand patterns. The current grid infrastructure will be unable to maintain reliable function as the system incorporates an even larger number of non-dispatchable renewable energy resources and encounters less predictable, rapidly changing load patterns. Grid-scale energy storage and other technologies that help to increase power system flexibility are therefore critical to reaching renewable energy integration targets without compromising efficient, reliable and cost effective operation of the grid [1].

This talk illustrates the use of optimization based methods to provide insight into the analysis, design, and operation of a power system with large-scale storage integration. We first discuss optimal power flow (OPF) based models for storage dispatch and allocation throughout the network. We then exploit the structure of the optimization problem to form a storage subproblem that isolates the relationship between the storage variables and market based price signals. The storage subproblem is used to show that these price signals are critical factors in optimal storage dispatch and siting decisions [2].

The second part of the talk seeks to reduce the computationally complexity of the OPF+storage problem by proposing a simplified model that augments commonly used linearizations through the inclusion of a quadradic loss approximation. This so-called DC optimal power flow (DCOPF) with losses formulation is then used to analyze the role of real power losses in optimizing grid-scale storage integration. We demonstrate the accuracy and improved computationally tractability of this method through case studies using a wind integrated test system [3].

[1] A. Castillo and D. F. Gayme, “Grid-scale energy storage applications in renewable energy integration: A survey," Energy Conversion and Management **87**, (2014) 885-894.

[2] A. Castillo and D. F. Gayme, “Profit Maximizing Storage Allocation in Power Grids," In *Proceedings of the 52nd IEEE Conference on Decision and Control*, pages 429-435 (Firenze, Italy, 2013).

[3] A. Castillo, X. Jiang and D. F. Gayme, “Lossy DCOPF for Optimizing Congested Grids with Renewable Energy and Storage," In *Proceedings of the American Control Conference*, pages 4342-4347 (Portland, Oregon, 2014).

Interaction between wind farms and the atmospheric boundary layer

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AND AMIN NIAYIFAR

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Key words: Wind farms, Wakes, Large-eddy simulation, Analytical modeling, Wind-tunnel experiments

Accurate prediction of atmospheric boundary layer flow and its interactions with wind turbines is of great importance for optimizing the design (layout) and control of wind farms. The first part of this presentation focuses on recent efforts to develop and validate a large-eddy simulation (LES) framework for wind-energy applications. The subgrid-scale turbulent fluxes of momentum and heat are parameterized using tuning-free Lagrangian scale-dependent dynamic models. The turbine-induced forces are parameterized using two types of models: an actuator disk model that allows for non-uniform force distribution and includes rotational effects, and an actuator line model. The LES code is validated against wind-tunnel measurements collected inside and above a large model wind farm. Overall, the characteristics of the wind-farm wakes simulated with the proposed LES framework are in good agreement with the measurements. Moreover, LES is also found to provide reasonable predictions of turbine power output in simulations of flow through an operational wind farm. In the second part of the presentation, a new analytical model of wind turbine wakes and wind farm wakes is introduced and validated against LES, wind tunnel measurements, and wind-farm power output data. It assumes a self-similar Gaussian shape of the velocity deficit and satisfies conservation of mass and momentum. The interaction between wakes is modeled using the velocity deficit superposition principle. Reasonable agreement is obtained between the proposed analytical model, LES results, and field data. This prediction is also found to be substantially better than the one obtained with a commonly used wind farm wake model.

Session Abstracts

Full field observation of dynamic wakes by means of long-range lidar measurements

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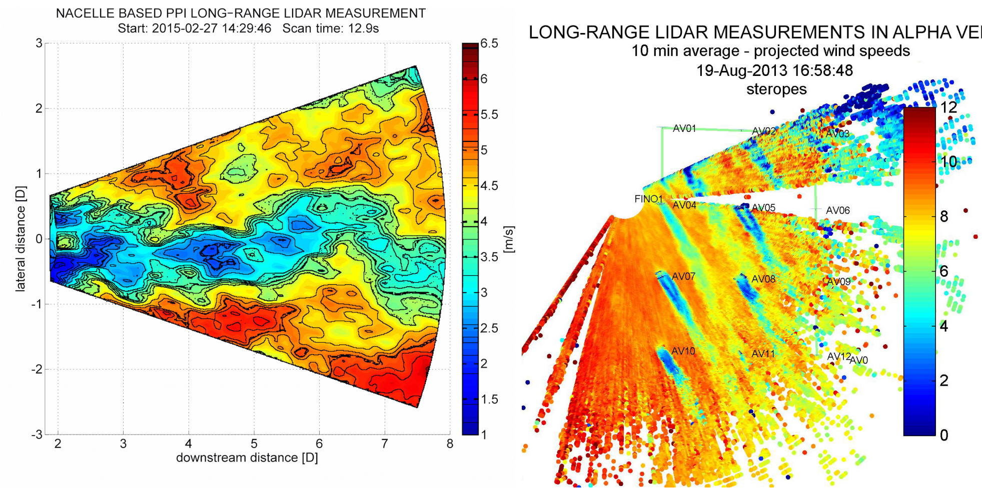
Key words: Nacelle lidar, multi-lidar offshore measurements, wake analysis, wake dynamics

Profound understanding of the behaviour of wind turbine wakes has become a necessity to the wind energy community. In the research area of wind farm operation and control as well as wake analysis new concepts are being developed which require higher accuracy and resolution in terms of time and space. The new envisaged applications rely on short-term prediction of dynamic flow conditions inside the wind farm. This contrasts with traditional applications, such as wind farm energy calculation where steady flow conditions are needed. In this respect a thorough full field validation has to be performed. For this, lidar measurement techniques can provide experimental data needed in the development and testing of the desirable tools. In this contribution we present first results of a measurement campaign with a long-range lidar on the nacelle of a multi-MW wind turbine of 115m rotor diameter and results from a multi-lidar measurement campaign at the offshore wind farm 'alpha ventus'. The aim is to produce high quality data of the wake with high resolution in time and space, which enables to validate and develop models in different areas. The measurements were performed with two different setups. On the one hand two long-range lidar systems installed at the nacelle of the wind turbine and on the other hand three long-range lidar systems were positioned at different locations within the offshore wind farm. In Figure 1a it can be observed a single horizontal scan of wake measurements. It has been measured by scanning downstream with a constant elevation. Figure 1b shows a low elevation long-range PPI scan of 'alpha ventus' containing multipe single wakes.



(a) (b)

Figure 1: (a) Single nacelle-based PPI-scan in the wake of a multi-MW wind turbine. Ranges: 228m to 912m, 5m resolution, azimuth: -20° to 20°, 0,3° resolution. (b) 10min average of PPI-scans from lidar system located at FINO1. Range: 100m to 3000m, 15m resolution, azimuth: 170° in total, 0.5° resolution.

Full scale wake experiments at Horns Rev – The case of downregulation

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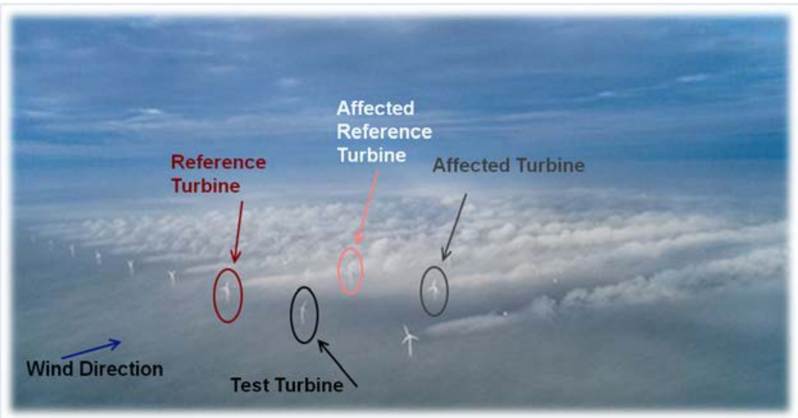
Key words: Wind farms, Downregulation, Real-time wake model, Available Active Power

Available (or Possible) Power is the power that a turbine or a wind power plant would produce if it had not been down-regulated (or curtailed). While down-regulation, either mandated or to sell reserve power as ancillary service, is getting more frequent, to determine exactly the available power of a down-regulated wind farm in real time is a difficult task. The PossPOW project is addressing that need, aiming to develop a verified method for the real-time estimation of the available power of a down-regulated offshore wind power plant (see posspow.dtu.dk).

While the estimation of the available power for a single turbine is state of the art, the sum of those available powers from all turbines in a wind farm overestimates the power due to the reduced wake effects during down-regulation. In order to calculate that effect, the equivalent wind speed over an entire wind turbine rotor is estimated from the produced power, the pitch angle and the rotor speed using the Cp curve. A real-time wake estimation of normal operation is then performed and advected to the next downstream turbine, and so on until the entire wind farm is calculated.

The estimation of the rotor equivalent wind speed, the parameterisation of the GCLarsen wake model for real-time use (i.e., 1Hz data from Horns Rev and Thanet) and the details of the advection are the topic of another paper in these proceedings by Göcmen et al. Here we describe the experiments using the Horns Rev wind farm for the verification of the algorithm, where in the proper wind conditions the first turbine to see the incoming wind is down-regulated and the effects on the turbines behind it are assessed. Assuming similarity of the wind speeds between neighbouring rows of turbines, the power produced by the second turbines in the line can be compared when some of the front row turbines are down-regulated. To get a good signal, a trigger mechanism is employed which assures that the experiment is only started if the wind is blowing directly down the line of turbines while the turbine is in the ascending part of the power curve. The experiments are currently being run, the first ones have been analysed.



Model-based wake tracking using lidar measurements for wind farm control

Steffen Raach[1], **David Schlipf**[1], **Juan José Trujillo**[2], **Po Wen Cheng**[1]

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Key words: Wind farm control, wake measurements, wake tracking, lidar.

Wake interactions in wind farms cause a reduction in power capture and higher structural loads on the turbines. Steering wakes away from downstream turbines offers a significant potential for improving the performance of a wind farm [1]. Previous results have been obtained under controlled conditions in numerical and wind tunnel experiments. In the full field, these quantities and thus the resulting wake behavior are difficult to know beforehand. In this work, a model-based method is presented to measure the wake displacement, direction and recovery from nacelle-based lidar measurements. This approach would enable feedback control of the wake displacement. The wake characteristics are identified by fitting a model of the wind field behind the rotor to measured line-of-sight wind speed from a lidar system. The wind field is modeled as a superposition of the rotor effective wind speed v_0, the linear vertical shear δ_V, and a 3D wake deficit model Ψ_{wake}. The wind field model is rotated with the horizontal inflow angle α_H and Ψ_{wake} is translated by the horizontal displacement of the wake y_{wake} [2]. The wake deficit at the rotor plane is modeled with an initial momentum p_{wake} and the mixing of p_{wake} is obtained by applying a 2D transfer function, which is parameterized by the recovery rate ϵ_{wake}. In this way, the wind field behind the rotor is modeled using a parameter set $s = [v_0, \delta_V, \alpha_H, y_{wake}, \epsilon_{wake}, p_{wake}]$. With a lidar simulation, the line-of-sight wind speed $\hat{v}_{los}$ can be calculated for each set s and compared to the measured v_{los}. The wake characteristics are obtained by solving an a prediction error minimization problem

$$\min_s J \quad \text{with} \quad J = \sum_i^n \frac{1}{n} \left(\hat{v}_{los,i} - v_{los,i}\right)^2 , \tag{1}$$

where n is the number of measurements of a full scan. The method is applied to data from a scanning lidar system with $n = 245$ over 8 s to track the wake of a commercial 5MW wind turbine, see Figure 1.

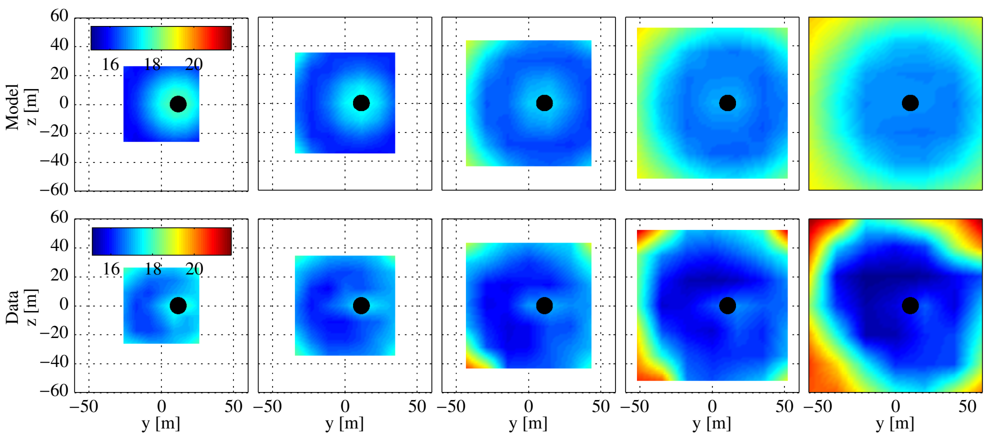

Figure 1: Comparison between modeled (top) and measured wind speeds (bottom). Wake displacement (dots).

[1] P. M. O. Gebraad, F. W. Teeuwisse, J. W. van Wingerden, P. A. Fleming, S. D. Ruben, J. R. Marden, and L. Y. Pao. “Wind plant power optimization through yaw control using a parametric model for wake effects - a CFD simulation study,” Wind Energy, 2014.

[2] J. J. Trujillo, J. K. Seifert, D. Schlipf, I. Würth, and M. Kühn “Impact of wind turbine yaw misalignment on the near wake deviation measured in the full field,” In preparation for submission to Journal of Wind Engineering and Industrial Aerodynamics.

Application of dynamic time warping in wake tracking analysis

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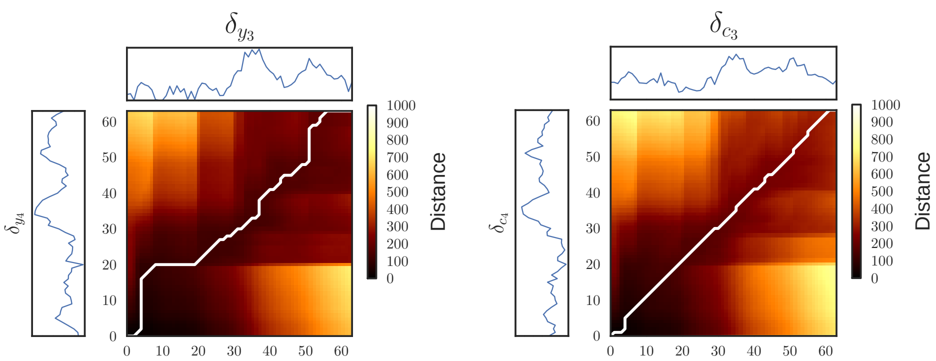
Key words: Wake tracking, nacelle lidar, wake advection, dynamic time warping

Wake tracking techniques based on lidar measurements have been developed to capture large scale dynamics of wind turbine wakes. Initial implementations were aimed at obtaining time series of transversal wake position at defined downstream distances. Further development has been achieved through implementation of quasi-simultaneous measurements at several downstream stations. The time series at consecutive stations can be analysed by means of cross-correlation in order to find a time shift between them. As result a wake advection speed can be estimated which can be used for development and validation of meandering wake models. This technique assumes that the time series between downstream stations may differ in amplitudes but not in time characteristics. In order to assess the validity of this assumption, we apply dynamic time warping (DTW). This provides an optimised element-wise alignment, or warping path, of the time series. We propose to explore the topology of the warping path in order to assess time series similarity.

The DTW technique is applied here to evaluate near wake tracking of an offshore wind turbine. Two time series of wake offset (δ) at 1.0 and 1.2 diameters behind the turbine are analysed. These are obtained in an azimuthal frame of reference parallel to the turbine rotor. For both time series, cross-correlations and DTW are performed for only the horizontal plane component (Fig. 1(a)) and for the full azimuthal vector (Fig. 1(b)). For these two data sets the wake advection speed, estimated by cross-correlation time lag, is u_a=1.9 m/s and u_a=1.6 m/s, respectively. Fig. 1 shows the Euclidean distance between data points, along with the minimal cumulative distance path or warping path in white. The latter indicates a higher similarity of the wake offset time series for the azimuthal vector (Fig. 1(b)) due to less deviation from the diagonal. Therefore, the azimuthal representation is interpreted as a more accurate wake advection indicator. The results suggest that DTW can reveal features of the correlation of wake tracking time series, which otherwise are not easy to discern from comparison of normalized correlation coefficients. The technique shows potential for complementing the systematic analysis of wake tracking in regards to characterisation of wake advection speed.



(a) Horizontal (ρ=0.95, u_a=1.9 m/s) (b) Azimuthal (ρ=0.92, u_a=1.6 m/s))

Figure 1: Ten minute wake offset time series at 1.0 and 1.2 diameters downstream (subscripts 3 and 4, respectively). Colormap shows the Euclidean distance of DTW along with the minimised warping path (white).

Coupling fluid dynamic and economic wind farm models to determine optimal wind turbine spacing

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Key words: Wind farms, Economic Optimization, Coupled wake boundary layer model

Now that wind-farms are becoming increasingly larger, the economics and physics of wind farms become intrinsically coupled and important when designing large wind farms. It is important to develop wind farm models in which economic considerations can be combined with physical considerations in a transparent and intuitive way. For smaller wind-farms the majority of the turbines can be placed such that physical wake effects are relatively limited and thus wake effects may be less important. However, for large wind farms (e.g. with many hundreds of turbines) it is important to consider the influence of wake effects on the optimal turbine spacing. In this work we combine economic and fluid dynamic models to determine the main parameters that are important for the design of very large wind-farms.

We expand the method used by Meyers and Meneveau [1] to determine the optimal turbine spacing in a very large wind-farm. The influence of several additional aspects, such as cable costs, maintenance costs, the wind-farm layout, and the effect of optimizing net revenue instead of normalized power per unit cost, are addressed. In agreement with prior results [1], we show that without cable costs the optimal turbine spacing strongly depends on the turbine to surface (land or sea surface) cost ratio (α), leading to spacings significantly larger than currently used for typical values of α. However, when realistic cable costs are included, the obtained optimal spacing can be smaller, approaching the commonly used spacings. Additional space reduction can be expected when including maintenance costs, specially in the case of off-shore wind farms.

To assess the influence of the wind-farm layout on the optimal spacing we evaluate the optimal spacing for aligned, staggered, and “best" array layout using the capabilities of the Coupled Wake Boundary Layer (CWBL) model [2] which couples the Jensen model [3] to the top-down model for very large wind farms. The differences in the optimal spacing for the staggered, aligned and “best" array layout are analyzed and discussed. The same considerations can be extended to maximizing profitability rather than power per unit cost.

We further present results that include costs associated with loading that are proportional to the turbulence intensity levels in the wakes. We examine the capabilities of the CWBL model to provide predictions for turbulence intensity as function of wind farm parameters and then use the results in the optimization approach. It is recalled that for the design of an actual wind-farm local effects and restrictions should always been taken into account. However, an analytical analysis such as presented here is useful to provide insights about the main trends and to develop intuition of the factors that are important for the design of wind-farms.

Acknowledgments: Research supported by the Dutch FOM, and US NSF (grant IIA-1243483, WINDINSPIRE).

[1] Meyers & Meneveau. Optimal turbine spacing in fully developed wind farm boundary layers. *Wind Energy*, **15**, 305, 2012.
[2] Stevens, Gayme & Meneveau. Coupled wake boundary layer model of wind-farms. *J. Renewable and Sustainable Energy*, (in press) 2015.
[3] Jensen. A note on wind generator interaction. *Risø-M-2411, Risø National Laboratory, Roskilde*, 1983.

Parameter Variation for Maximizing the Power Production of a Model Wind Farm

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Key words: Wind farms, Interaction, Control, Experiment, Wind Tunnel

During the last years a series of model scale wind tunnel experiments investigating wind turbine wake interactions have been realized at NTNU's department of Energy and Process Engineering. A number of well-defined "blind test cases" have been selected and provided to developers of numerical codes to verify their simulation method without knowing the results a priori. Besides the power production and the thrust force, the mean and turbulent flow characteristics in the wake behind one and two model turbines in different setups were compared and documented in comprehensive publications [1], [2] and [3].
Recently, a new series of experiments focusing on the optimization of the total power output has been carried out. For this purpose, a number of parameters such as the turbines' tip speed ratios, axial separation distance, as well as the inlet conditions have been systematically varied. Three main test cases have been performed varying the inlet condition to the test section: a 1st case with very low turbulence (TI=0.23%), a 2nd case with grid generated turbulence (TI=10%) and a 3rd case with a turbulent shear flow (TI=10%) is approaching the upstream turbine. Of this comprehensive database, a number of relevant test cases have been selected and provided to comparison with numerical codes in a fourth blind test.
The experiments showed significant differences of the inlet turbulence levels on the wake recovery and thus the power production of the downstream turbine. Adding shear to the inlet flow primarily was seen to influence the mean velocities profiles in wake. An increase in axial separation distance from $x = 3D$, to $x = 5D$ and up to $x = 9D$ revealed a significant increase in combined power output. A slight variation from the first turbine's design tip speed ratio is able to benefit the combined power output of the two turbines. As can be seen in the rather flat top surface in Figure 2, variations from the design tip speed ratio of both turbines influence the total power coefficient only insignificantly. This implies that the total power production of this model test case is quite stable and not very susceptible to deviations from the optimum rotational speed.

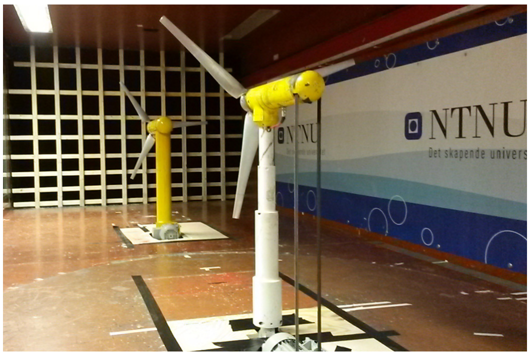

Figure 1: Two model wind turbines in exposed to a grid generated shear flow

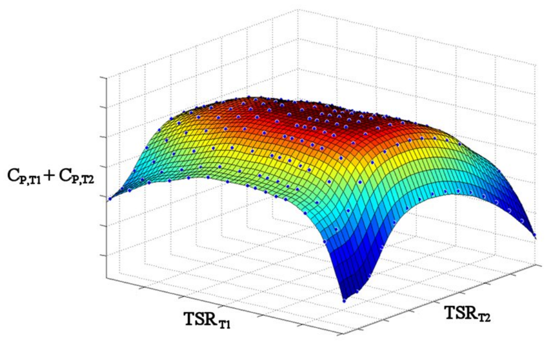

Figure 2: Combined power ($C_{P,T1} + C_{P,T2}$) dependent on tip speed ratio variations of the individual turbines

[1] P-Å. Krogstad, P.E. Eriksen "Blind test calculations of the performance and wake development for a model wind turbine", Renewable Energy, 50, 2013, pp. 325-333
[2] F. Pierella , P-Å. Krogstad, L. Sætran "Blind Test 2 calculations for two in-line model wind turbines where the downstream turbine operates at various rotational speeds" Renewable Energy, 70, 2014, pp. 62-77
[3] P-Å. Krogstad, L. Sætran, M.S. Adaramola, "Blind test3 calculations of the performance and wake development behind two in-line and offset model wind turbines", Journal of Fluids and Structures, 52, 2015, pp. 65-80

Performance monitoring by tracking estimated power curves on a wind farm level

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Key words: Monitoring, Performance, Power curve

Wind farm operators are interested most in the performance of a wind turbine, and more specific in the possible production loss. In this contribution results are shown for the Belwind offshore wind farm outside the Belgian coast. The data used during this campaign is coming entirely from the SCADA of the turbines.
A well-known parameter to detect performance issues is the availability (time-based or production-based). Since the availability is highly affected by down-time, small changes in production are usually not detected by the availabilities. To detect these small changes one can make use of the power curve, which represents the relation between windspeed at the turbine and power production of the turbine. This relation is illustrated in Figure 1. By calculating the power curve on regular basis using data during normal operation and defining a health index related to the power curve, one can track the power curve over time. This health index compares the calculated power curve to the warranted power curve and gives an idea of lost energy during normal operation by the wind turbine.
By using this health index a seasonal change in the turbine performance was observed and underperforming turbines are easily detected.
To quantify the evolution in time, a linear model can be fitted for each turbine using the resulting values for the health index of several previous time frames. The resulting slopes can be compared to each other, on a wind farm level, and turbines degrading fastest in time compared to the others can be easily detected.

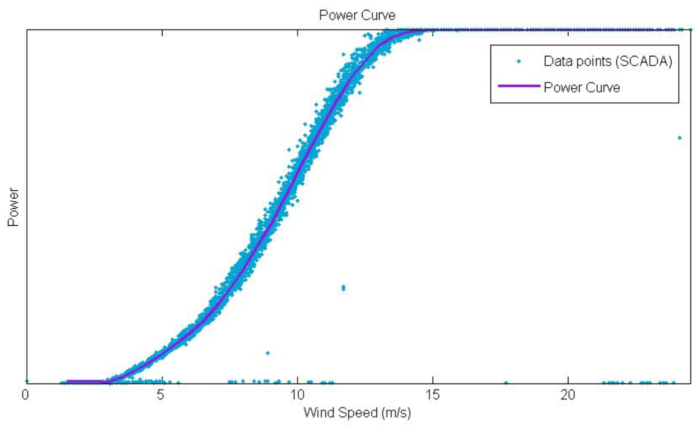

Figure 1: Example of a power curve

Multidisciplinary Research on Wake Control in Wind Power Plants at NREL: Wake Modeling and Control, Systems Engineering, and Field Testing

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Key words: Wind Power Plants, Wake Modeling and Control, Systems Engineering

Wind turbines in wind power plants impact each other's performance through their wakes. This interaction may reduce the total power output of the plant. This effect can be mitigated through plant layout optimization and wake control. Wake control techniques have different ways of using the turbine degrees of freedom to affect the wakes. Most wind plant control studies in the literature use axial-induction-based control [1], in which generator torque or blade pitch is altered to optimize wake velocities. Alternatively, yaw offsets are used to redirect the wakes and steer them away from downstream turbines. In [2], we compared the effectiveness of both approaches using the Simulator fOr Wind Farm Applications (SOWFA), a high-fidelity large-eddy simulation of the wind flow in a plant, coupled with a wind turbine aeroelastics model via an actuator line rotor representation [3]. We found that yaw control was more effective at improving wind plant power output; however, these results may depend on the simulated atmospheric conditions and turbine characteristics.

For yaw-based wake control, TU Delft and NREL developed an optimization strategy based on the FLORIS control-oriented model [4]. FLORIS predicts the steady-state wake redirection resulting from yaw, the wake expansion and recovery, and the power of each turbine in the wind plant. The FLORIS-based yaw control approach has been successfully tested in an online implementation in SOWFA [4]. Results show that in addition to being able to increase power, yaw offsets can reduce fatigue loads on both upstream and downstream turbines. Currently, we are analyzing field data from the CART3 turbine to validate the simulation results on the load effects of yaw, and are preparing to validate the wake control results on real wind plants.

In [5], FLORIS was extended to capture the effects of axial-induction-based wake control by adding corrections of wake recovery as a function of turbine power extraction and wake overlap. Another extension of FLORIS is FLORIDyn, which includes a dynamic model of the wake propagation through the flow field [6].

In [7], we performed wind plant systems engineering by combining optimization of layout and yaw control based on the FLORIS model. We are now coupling FLORIS with a more accurate rotor model based on blade element momentum theory. The coupled model will be used for combined optimization of rotor design, wind plant layout, and control.

[1] T. Knudsen, T. Bak, and M. Svenstrup, "Survey of wind farm control—power and fatigue optimization," Wind Energy, 2014.

[2] P. M. O. Gebraad, P. A. Fleming, and J. W. van Wingerden, "Comparison of actuation methods for wake control in wind plants," *Proceedings of the American Controls Conference*, Chicago, USA, 2015.

[3] NWTC Information Portal: SOWFA. https://nwtc.nrel.gov/SOWFA, 2015.

[4] P. M. O. Gebraad, F. W. Teeuwisse, J. W. van Wingerden, P. A. Fleming, et al. "Wind plant power optimization through yaw control using a parametric model for wake effects—a CFD simulation study," Wind Energy (2014).

[5] J. Annoni, P. M. O. Gebraad, A. K. Scholbrock, P. A. Fleming, and J. W. van Wingerden "Analysis of axial-induction-based wind plant control using an engineering and a high-order wind plant model," to appear in Wind Energy (2015).

[6] P. M. O. Gebraad, P. A. Fleming, and J. W. van Wingerden, "Wind turbine wake estimation and control using FLORIDyn, a control-oriented dynamic wind plant model," *Proceedings of the American Controls Conference*, Chicago, USA, 2015.

[7] P. A. Fleming, A. Ning, P. M. O. Gebraad, and K. Dykes, "Wind plant system engineering through optimization of layout and yaw control," Wind Energy (2015).

Optimal coordinated control of energy extraction in wind farms

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Key words: Wind farms, Large-Eddy Simulation, Optimal Control

In very large wind farms the total vertical turbulent interaction with the atmospheric boundary layer plays an important role in the overall energy extraction of the wind farm [1]. In the current study, we investigate optimal control of wind-farm boundary layers, considering the individual wind turbines as flow actuators. By controlling the thrust coefficients of the turbines as function of time, the energy extraction can be dynamically regulated with the aim to optimally influence the flow field and the vertical energy transport. To this end, we use Large-Eddy Simulations (LES) of wind-farm boundary layers in a receding-horizon optimal control framework, where the control model is simply the full set of LES equations, and the optimal control is performed given a full interaction with the space-time flow state. Such an approach is not practicable in real life, as the LES optimal control problem is by many orders of magnitude too expensive to solve in real time. However, the optimal control results obtained in such an approach may yield many new insights into how to control wind-farm boundary layers for maximum energy extraction, and the related physical mechanisms of energy exchange. Given the complex and very high-dimensional nature of this control problem, such insights are not simply deduced using basic fluid mechanics principles or intuition. In a first step, the optimal control of an 'infinite' wind-farm boundary layer is studied [2]. We find that the energy extraction is increased by 16% compared to the uncontrolled (greedy) base case. In the controlled case the dispersive stresses increase drastically, while the Reynolds stresses decrease on average, but increase in the wake region, leading to better wake recovery. This is directly related to an increase of the vertical fluxes of energy towards the wind turbines. We further find that the turbine control signal is slightly anti-correlated with the incoming turbulent flow, thus actively increasing the turbulence in the wake. In a second step, the same type of optimal control methodology is applied to a developing wind-farm case with 10 turbine rows, which we implement in our pseudo-spectral solver SP-Wind using a fringe region technique, and a concurrent precursor method [3]. An increase in power extraction of 7% is obtained. The difference with the infinite case is partly attributed to the first row of turbines that cannot be optimized compared to the greedy case. Next to that, in order to save computational time, the optimization algorithm was terminated after fewer iterations. Nevertheless, the same physical mechanisms are identified that increase power extraction, i.e. improved wake recovery and wake mixing.

The authors acknowledge support from the European Research Council (FP7-Ideas, grant no. 306471). Simulations were performed on the computing infrastructure of the VSC Flemish Supercomputer Center, funded by the Hercules Foundation and the Flemish Government.

[1] M. Calaf, C. Meneveau, and J. Meyers "Large Eddy Simulation study of fully developed wind-turbine array boundary layers," Physics of Fluids **22**, 015110 (2010).

[2] J. P. Goit and J. Meyers, "Optimal control of energy extraction in wind-farm boundary layers," Journal of Fluid Mechanics **768**, 5-50 (2015).

[3] R. J. Stevens, J. Graham, and C. Meneveau, "A concurrent precursor inflow method for Large Eddy Simulations and applications to finite length wind farms," Renewable Energy **68**, 46-50 (2014).

Practical tools for optimisation of wind plant sector management strategies

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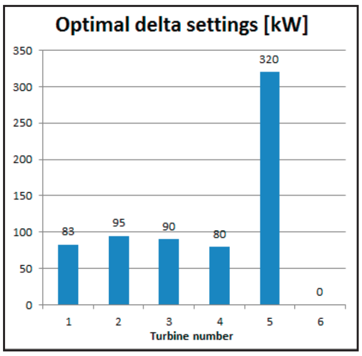
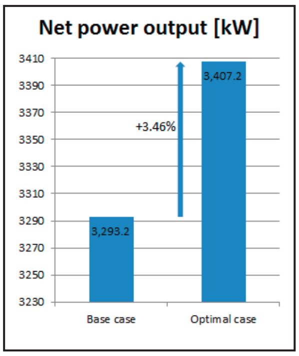
Key words: Wind farms, Wake interaction, Control, Sector management, Loads, Optimisation

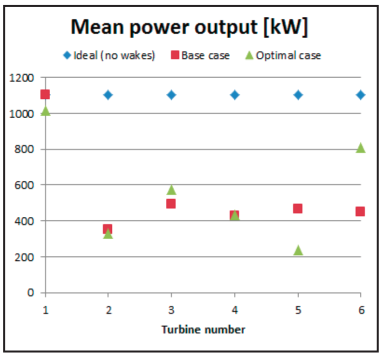
Wake interactions between individual turbines within a wind farm mean that optimal wind farm performance can only be achieved by a central controller acting at the wind plant level, rather than by each turbine controlling itself autonomously. In practice the individual turbine controllers continue to be used, but the set-points to which they operate are determined by the wind plant controller and changed according to the circumstances. In this way the plant level controller modifies the turbine wakes, and hence the operating conditions of downstream turbines. This can potentially increase energy capture, and also reduce turbine fatigue loads, leading to a reduction in the levelised cost of energy over the wind plant lifetime. The principles have been well known for many years [1], but a systematic way to design the optimal wind plant control strategy is difficult to formulate, partly due to the lack of suitable models. Hence crude sector management strategies are sometimes adopted, such as switching off every other turbine when the wind is blowing along a closely-spaced row to avoid unacceptably high loads.

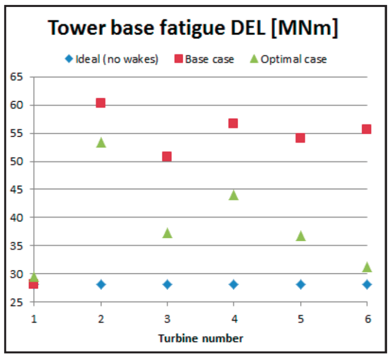
This paper presents an approach being developed at DNV GL in which a validated wind farm wake model from the *Windfarmer* code is combined with a database approach to the evaluation of fatigue loads derived from detailed turbine simulations using *Bladed*. Individual turbine set-points are changed using delta control functionality developed for grid support. A numerical optimiser adjusts the delta control set-points to minimise a cost function which trades off the benefit of energy production against the costs of fatigue loading on turbines and components. The cost function design depends crucially on the specific application: for example it will be quite different for pre-construction optimisation when there may still be scope to influence the capital cost of turbines and support structures by reducing the expected fatigue loading, while post-construction the reduced loading can only influence O&M costs and project lifetime.

Preliminary results for a simple generic wind farm indicate that considerable scope exists for increasing the energy output in certain wind conditions while simultaneously reducing loads, for example at the tower base. There is also scope for further improvement by also adjusting turbine yaw set-points since this affects the wake trajectories [2]. Next steps will include increasing the modelling accuracy, for example in respect of wake superposition and turbulence, including the effect of yaw misalignment, and time-domain representations for detailed evaluation of control strategies. Comparison of model predictions against high-fidelity CFD and wind tunnel and field measurements will build confidence in the feasibility of the approach.









[1] C. J. Spruce, "Simulation and Control of Windfarms", *PhD Thesis*, University of Oxford, 1993.

[2] P. Fleming *et al*, "Simulation comparison of wake mitigation control strategies for a two-turbine case", *Wind Energ. (2014) DOI: 10.1002/we.1810,* Wiley Online Library 2014.

Wind farm power optimization and control in highly variable multiple wake flows

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Key words: Wind farms, Wakes, Flow variability, Model-based data analysis, Operational wake-flow modeling, Optimization

A model-based optimisation approach is used to investigate the potential gain of wind-farm power with a cooperative control strategy between the wind turbines [1]. Based on the Jensen wake model with the Katic wake superposition rule, the potential gain for the Nysted offshore wind farm is calculated to be 1.4--5.4% for standard choices $0.4 > k > 0.25$ of the wake expansion parameter. Wake model fits based on short time intervals of length 15sec < T < 10min within three months of data reveal a strong wake flow variability, resulting in rather broad distributions for the wake expansion parameter. When an optimized wind-farm control strategy, derived from a fixed wake parameter, is facing this flow variability, the potential gain reduces to 0.3--0.5%. An omnipotent control strategy, which has real-time knowledge of the actual wake flow, would be able to increase the gain in wind-farm power to 4.9%.

In view of designing a suitable model-based operational wind-farm control, further data-driven analysis is presented, which includes the extraction of short-term coherent production patterns and the characterization of short-term noise patterns in a co-moving frame of reference.

[1] J. Herp, U.V. Poulsen and M. Greiner, “Wind-farm power optimization including flow variability", Renewable Energy (2015) to appear.

Frequency Regulation Controllers for Wind Farms — Preliminary Findings from Large-Eddy Simulations

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Key words: Wind farms, Frequency regulation, Ancillary services, Large-eddy simulations

As wind power production increases in many countries, generators that have traditionally provided frequency regulation services are displaced. Therefore, there is growing interest in using wind turbines and farms to provide these regulation services. Of particular interest is secondary frequency regulation, where participating generators track a power generation reference signal provided at several second intervals by power system operator for up to an hour [1]. Previous studies have developed controllers that operate at a sub-optimal condition and adjust the tip speed ratio and blade pitch angle to control the power production [2]. These controllers, however, assume that power coefficient curves generated under steady flow will hold during unsteady changes in tip speed ratio and blade pitch angle. Furthermore, these controllers are therefore mostly limited to standalone turbines because aerodynamic interactions between turbines through wake effects are not considered.

Development of frequency regulation controllers for large wind farms requires more sophisticated aerodynamic models of wind turbines and farms. In this study, we simulate wind turbines operating in a turbulent, neutrally-stable atmospheric boundary layer using large-eddy simulations [3] coupled with actuator line wind turbine models [4]. Traditional pitch controllers are used to follow step changes in power setpoints. The resulting turbine power output shows a large initial overshoot, which is consistent with previous numerical simulations and measurements [5]. The overshoot is caused by unsteady inertial effects in the aerodynamic reaction to the step change in blade pitch angle. Furthermore, significant wake effects are apparent in the power production of downstream turbines, beginning after one inter-turbine flow through time. These wake effects cause the overall farm power to settle below the reference signal. Both of these phenomena must be addressed in order to develop effective frequency regulation controllers.

An open-loop, discrete-time, observer-based controller is developed that controls pitch angle to adjust for unsteady aerodynamic effects. Simulations of turbines following step changes in pitch angle under uniform inflow are used to develop a observer plant model and controller that selects the blade pitch operating state to follow a given reference signal. This controller is validated under uniform inflow to reference steps, ramps, and PJM's regulation test signals and under turbulent inflow to steps. Controllers to manage turbine wake interactions are the focus of future work.

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[1] Y. G. Rebours et al., "A Survey of Frequency and Voltage Control Ancillary Services—Part II: Economic Features," IEEE Transactions on Power Systems **22**, 350 (2007).

[2] J. Aho et al., "A Survey of Frequency and Voltage Control Ancillary Services—Part II: Economic Features," In *Proceedings of the American Control Conference*, 3120, (IEEE, Montreal, 2012).

[3] R. J. A. M. Stevens, J. Graham, and C. Meneveau, "A Concurrent Precursor Inflow Method for Large Eddy Simulations and Applications to Finite Length Wind Farms," Renewable Energy, **68**, 46 (2014).

[4] L. A. Martínez-Tossas, M. J. Churchfield, and S. Leonardi, "Large Eddy Simulations of the Flow Past Wind Turbines: Actuator Line and Disk Modeling," Wind Energy (2014).

[5] J. N. Sørensen and A. Myken, "Unsteady Actuator Disc Model for Horizontal Axis Wind Turbines," Journal of Wind Engineering and Industrial Aerodynamics **39**, 139 (1992).

Improved onshore AC Grid Frequency & DC Grid Voltage Control from Offshore Wind Power Plants connected through HVDC using wind speed forecast

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Key words: Wind farm control, AC frequency control, DC voltage control, multi-terminal HVDC, wind speed forecasts

As variable speed wind turbines do not yet contribute to the system inertia and primary reserves extensively, it is expected that the frequency stability gets deteriorated as more and more conventional generation is displaced by wind. Therefore basic control methods to deliver inertia as well as droop control to mitigate severe frequency dips following large disturbances have already been developed in the literature [1].

Whereas these basic controllers only use the system frequency as input to the droop and inertial response controller, in this work also the wind speed forecast and operating point of the turbine are taken into account [2]. This will result in an improved support in case increased wind speeds are forecasted during the primary control phase of the system or can prevent the turbine to reach an unstable operating point when wind speed is expected to drop. The improved frequency support can in a first step be achieved by altering the gains of the primary frequency and inertial response controller of wind power plant (WPP) depending on the forecasted wind speed.

Multi Terminal DC (MTDC) system requires ancillary services from the associated DC equipment and AC grids to mitigate the oscillations in the DC voltage caused by certain disturbances and contingencies [3]. Therefore, the ability of the WPP participating in DC voltage control of the MTDC system is addressed in this work. Moreover, it is examined to what extend wind forecast can be taken into account to modify the associated controller’s gains which provide the additional power to mitigate the DC voltage variations in the MTDC system.

In this research, the control technique is applied to a large offshore WPP which is connected to the onshore system using MTDC system. As this connection electrically decouples the WPP from the rest of the system a communication-less scheme is developed whereby the DC voltage is used as a signal to transfer the onshore frequency variations to the offshore system.

[1] Xue Yingcheng, Tai Nengling, Review of contribution to frequency control through variable speed wind turbine, Renewable Energy, Volume 36, Issue 6, June 2011, Pages 1671-1677.

[2] De Rijcke, S., Tielens, P., Rawn, B., Van Hertem, D., Driesen, J. (2014). Trading Energy Yield for Frequency Regulation: Optimal Control of Kinetic Energy in Wind Farms. IEEE Transactions on Power Systems.

[3] Zeni, L, Glasdam, J, Hesselbæk, B, Lund, T, Sørensen, PE, Hansen, AD & Kjær, PC 2014, 'Coordinated system services from offshore wind power plants connected through HVDC networks'. in *CIGRE Session 45, 2014.*, C1-PS2 – C1_212_2014 NCA 535, International Council on Large Electric Systems.

Integrated Analyses of Demand Response, Wind Variability, and Markets

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Key words: Energy Markets, Capacity Markets, Wind Integration, Demand Response

As part of the WINDINSPIRE project, four interrelated projects have been underway at JHU to characterize how demand response, wind variability and forecast error, and short- and long-run power markets would interact, determining overall market performance in terms of costs, emissions, and reliability. In this talk, we highlight the conclusions of these projects, the implications of each project's results for the other projects, and their diverse methodologies.

Starting with the long view, we first ask the question: do common designs for energy and capacity markets in US support the efficient mixes of generation investment? We model how simplifications could cause market choices among wind, solar, and various thermal technologies to diverge from the least-cost mix that meets a stated reliability constraint. Examples of such simplifications include basing capacity credits on average (as opposed to marginal) contributions to meeting system net load peaks, or the use of expected output during peak periods to determine capacity payments.

Then narrowing our focus to short-term markets, we ask whether two settlement (day-ahead and real-time) spot markets for thermal and wind energy and demand response can yield efficient outcomes even if market operators use simplified (deterministic) rather than full stochastic models that capture the effects of wind and load forecast error. Our models show that efficient arbitrage between the two markets by generators or traders can result in optimal unit commitment schedules, correcting biases in operator decisions.

However, barriers to trade day-ahead or in real-time between adjacent geographic markets stand in the way of such efficiencies. A third analysis considers the relative value of linking day-ahead markets (as in the EU) versus linking real-time markets (as in the US West) in the face of price uncertainty caused by wind and load variations.

A major uncertainty in all of these analyses is the extent to which demand response can help deal with wind variations. In our final analysis, we focus on the actual performance of this key part of the market for wind energy. We analyze a large database from a critical peak pricing pilot project in California, and find that most of the roughly 15% decrease in peak residential load due to the pilot is due to price rather than information that a critical peak day is occuring. However, green households react much more to the provided information.

Together, these projects cover the scales of time (minutes to years), space (local to multiregional markets), and markets (from comprehensive supply-demand analyses to focussed studies of the actual performance of resources). Integrating these is key to understand the full implications of wind variability for the cost, reliability, and environmental performance of the power sector.

The impact of uncertainty on wind power forecasts on power system balancing: reserve sizing, allocation and activation

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Key words: Uncertainty, wind power, balancing, reserves, reserve sizing, reserve allocation, reserve activation

Electricity generation from renewable energy sources (RES) has risen considerably over the last decade. The integration of such a massive amount of RES-based electricity generation in the power system leads to so-called *integration or system costs*, which are the result of some specific properties of RES. For example, some forms of RES, such as wind, are only limitedly predictable. As generation systems are planned before real-time, deviations from what is expected – e.g. forecast errors – need to be overcome with up- or downward regulation of dispatchable generation, load or storage. The associated operational costs are referred to as *balancing costs*.

We will employ a stochastic modeling framework to study and evaluate the impact of intermittent wind power on this balancing cost, expanding our work presented at the 37th IAEE Int. Conf. [1]. This hybrid stochastic unit commitment (UC) model seeks to minimize the expected operational cost associated with generating the demanded electricity, given a large set of wind power forecast error scenarios [2]. By comparing the resulting operational cost under forecast conditions to the cost obtained from a UC model in which no reserves are maintained, one obtains a proxy for reserve allocation cost. These are costs incurred by the system to keep capacity available for up- and downward regulation. The expected operational cost of the stochastic UC is compared with an expected cost obtained from simulations in which perfect foresight on the wind power forecast error is assumed, in order to obtain a proxy for the balancing cost, i.e. the sum of the activation and allocation costs. As a case study, we will study the balancing cost of wind power forecast errors in a system inspired by the Belgian electric power system. Four representative weeks are selected, assuming a wind energy penetration level of 30% (annually, energy basis), using (scaled) wind and demand data for the year 2013. A full description of the proposed framework can be found in [2], including a description of the case study.

Over the four selected weeks, allocation costs vary between 0.4 €/MWh wind and 6.0 €/MWh wind. At higher wind energy penetration levels, capacity with low variable costs can be used as reserve capacity, lowering the reserve allocation costs. Note that this capacity is typically less flexible, which leads to high volumes of curtailment. In addition, wind power can participate in the reserve requirements. Activation costs are between -1.2 €/MWh wind and 0.8 €/MWh wind and are highly dependent on the availability of regulating capacity with low variable costs (e.g. scheduled curtailment or storage). Note that activation costs can be negative: when the wind power production exceeds the forecast, fuel and carbon costs can be avoided in other conventional units. The balancing cost, i.e. the sum of the allocation and activation costs, can however not be negative and varies between 0.6 €/MWh wind and 5.4 €/MWh wind.

[1] K. Bruninx, E. Delarue and W. D'haeseleer, "The cost of wind power forecast errors in the Belgian power system," In *Proceedings of the 37th IAEE Int. Conf.*, (New York, USA, 2014).

[2] K. Bruninx, K. Van den Bergh, E. Delarue and W. D'haeseleer, "Optimization and allocation of spinning reserves in a low carbon framework," Accepted for publication in IEEE Trans. on Power Systems, (2015).

Redispatching in an interconnected electricity system with high penetration of offshore wind

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Key words: Offshore wind integration, Congestion management, Redispatching.

Grid congestion management is gaining importance in certain parts of the European electricity grid. The deployment of renewable electricity sources at locations with a weak grid connection and far from the load centers, e.g., offshore wind farms, can lead to overloading of transmission lines. Redispatching, i.e., rearranging scheduled generation and consumption, might be needed to obtain a feasible and safe operational state of the electricity system. Redispatching is a rather new phenomenon for system operators in certain countries. Therefore, there is a need for a thorough understanding of redispatching triggered by offshore wind generation.

This study investigates the impact of three parameters on the redispatching quantities and costs: (1) an increase in offshore wind generation, (2) loop flows through the electricity system, and (3) a curative and preventive N-1 security criterion.

Towards this aim, a dedicated generation scheduling model is developed, consisting of a day-ahead market and a redispatch phase. The Belgian 2016 electricity system is considered as case study. Belgium is an exemplary case to illustrate congestion issues that can arise due to the deployment of offshore wind. Belgium aims to integrate a considerable amount of offshore wind generation, but the current grid connection between the shore and the main load centers is rather weak, causing grid congestions.

Three general conclusions can be drawn from this study. First, transmission grid constraints might restrict the deployment of offshore wind generation. Second, it is important to consider loop flows when quantifying redispatching, especially in a highly interconnected electricity system as the European system. The case study shows that loop flows can more than double the need for redispatching. Third, relaxing the N-1 security criterion in congested grid areas from preventive to curative can drastically reduce the redispatch costs. These conclusions can be used by the grid operator to accommodate offshore wind, without jeopardizing the safe operation of the electricity grid.

The Active Participation of Wind Power in Operating Reserves

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Key words: balancing, operating reserve, probabilistic forecasting, unit commitment, wind power

The increasing share of variable renewable energy sources for electricity increases the operating reserve requirements of power systems [1]. Meanwhile, research and demonstration projects have shown that wind power is able to meet the technical requirements of providing reserve capacity as an ancillary service [2]. This contribution studies the techno-economic feasibility of procuring reserve capacity as an ancillary service from wind power generators. An economic framework is put forward describing the revenues and costs of procuring up- and downward reserve capacity from wind power, as well as the market framework describing the potential participation of wind power in present ancillary service markets.

Research shows that acceptable availability levels can be achieved when contracting reserve capacity on day-ahead markets, by means of probabilistic forecast models. The participation of wind power is analyzed with a unit commitment model in order to determine the impact on generation system scheduling, as well as the electricity generation costs [3]. Simulations show how wind power does become a potential provider of downward reserve capacity when facing high reserve capacity requirements during periods with low demand and high renewable generation. In contrast, it's potential in the upward reserve capacity remains limited, explained by the high opportunity cost.

[1] De Vos, K., Morbée, J., Driesen, J., Belmans, R. 2013. "Impact of Wind Power on Sizing and Allocation of Reserve Requirements". IET Renewable Power Generation, 7 (1), pp. 1-9

[2] Tielens P., De Rijcke S., Srivastava K., Muhamad R., Antonis M., Driesen J. 2012. "Frequency Support by Wind Power Plants in Isolated Grids with Varying Generation Mix". Power and Energy Society General Meeting 2012, San Diego, USA, 22-26 July 2012.

[3] De Vos, K., Petoussis, A., Driesen, J., Belmans, R. 2013. "Revision of reserve requirements following wind power integration in island power systems". Renewable Energy: An International Journal, 50, pp. 268-279.

Predicting wind power markets: a new generation of climate risk management tools

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Key words: Wind power, Market behaviour, Risk management, Climate services

Early identification of market vulnerabilities, risks and opportunities can minimise subjective decision-making and facilitate calculated and precautionary action[1].

To anticipate the behaviour of the wind power market over monthly to annual timescales, current practices use the retrospective climatology to evaluate future wind power variability, with an assumption that the past will also represent the future. Recent advances in climate predictions can provide a more informative view[2] by modelling future wind over long-term trading timescales: they use both an analysis of the past climate system, as well as its current state at the specific time when the prediction is created to provide a probability of different future outcomes, with an indication as to which will be the most likely. It has been demonstrated that climate predictions can improve upon the use of climatology at some spatial and temporal scales[3], so energy traders now have a new set of climate risk management tools that can strengthen their decision-making, but are they ready to use them?

Climate predictions come with a new set of challenges for end users: information is often un-tailored and hard to understand or apply in a decision-making context[4]. The next generation of European energy and climate projects, including NEWA, SPECS and EUPORIAS aim to address these challenges and support the development of a new realm of climate services and tools based on climate predictions. Here we will present the state-of-the-art in wind power prediction research and services development for the energy markets, to help end users assess and validate the usefulness of climate predictions within their strategic decision-making processes, as well as new visualisation tools and interfaces tailored to the energy sector to facilitate their application.

The projects referred to are NEWA (www.euwindatlas.eu), EUPORIAS (www.euporias.eu) and SPECS (www.specs-fp7.eu), funded by the European Commission under the Framework Seven Programme.

[1] M. Marquis, "Weather, climate, and the new energy economy", Bull. Amer. Meteorol. Soc. **92** (2011)

[2] F.J.Doblas-Reyes, J. García-Serrano, F. Lienert, A.P. Biescas and L.R. Rodrigues, "Seasonal climate predictability and forecasting: status and prospects." Wiley Interdisciplinary Reviews: Climate Change **4.4**, 245-268 (2013)

[3] F.J. Doblas-Reyes, A. Weisheimer, M. Déqué, N. Keenlyside, M. McVean, J.M. Murphy, P. Rogel, D. Smith and T.N. Palmer, "Addressing model uncertainty in seasonal and annual dynamical ensemble forecasts", Quart. J. Roy. Meteor. Soc. **135**, 1538-1559 (2009)

[4] A. Kirtman and A. Pirani, "The state of the art of seasonal prediction," Bull. Amer. Meteor. Soc. **90**, 455–458 (2009)

Testing the coupled wake boundary layer model with LES of turbulent flow in widely spaced wind-farms

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Key words: Wind farms, Coupled wake boundary layer model, Large eddy simulations

Two common wind-farm modeling approaches are wake models and the top-down model. Wake models [2] approximate the growth of velocity deficits behind each turbine as linear and account for wake-wake interactions through superposition of squared velocity deficits. This approach captures the entrance effects well, but is less accurate in modeling the deep-array effects. Top-down models [1] are able to capture the coupling between the wind-farm and the atmospheric boundary layer, but do not capture the effects of relative turbine positioning. The Coupled Wake Boundary Layer (CWBL) model [3] introduces a two-way coupling between these approaches and provides improved predictions over its constitutive models.

To test the CWBL model under conditions where it has not yet been evaluated, we model turbulent flow in wind-farms that consist of a regular array of wind-turbines. We consider wind-farms with ten (or more) rows in the streamwise direction in order to study the fully developed regime. This number of turbine rows ensures that the power output of the later rows is approximately constant in both aligned and staggered wind-farm configurations. The distances between wind-turbines are $s_x D$ and $s_y D$, where D is the turbine diameter, in the streamwise and spanwise directions, respectively. We vary the streamwise spacing in the range $\sim [3.5, 36]$ and the spanwise spacing in the range $\sim [3.5, 12]$ and consider different combinations of these spacings in these parameter ranges. The inflow in our simulations is obtained using a concurrent-precursor method [4] and the turbines are represented by an area averaged actuator disk model using a constant thrust coefficient C_T, which is representative of turbines operating in region II. Figure 1 shows a sample comparison of LES and CWBL model predictions. The various comparisons to be presented show that the CWBL model reproduces the LES results under many conditions. Conditions under which discrepancies exist are also identified and discussed.
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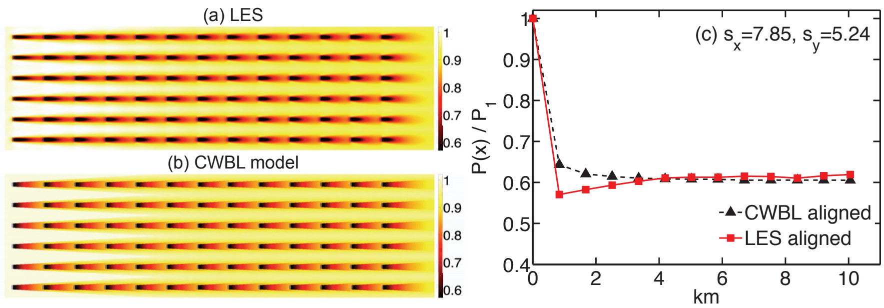

Figure 1: Normalized velocities at hub-height obtained in (a) LES and from (b) the CWBL model for an aligned wind-farm with $s_x = 7.85$ and $s_y = 5.24$. (c) Corresponding normalized power output $P(x)/P(1)$ development. Figure from Ref. [3].

[1] Frandsen, Barthelmie, Pryor, Rathmann, Larsen, Højstrup, Thøgersen. Analytical modelling of wind speed deficit in large offshore wind farms. *Wind Energy*, **9**:39–53, 2006.
[2] Jensen. A note on wind generator interaction. *Risø-M-2411, Risø National Laboratory, Roskilde*, 1983.
[3] Stevens, Gayme, Meneveau. Coupled wake boundary layer model of wind-farms. *J. Renewable and Sustainable Energy*, 2015.
[4] Stevens, Graham, Meneveau. A concurrent precursor inflow method for Large Eddy Simulations and applications to finite length wind farms. *Renewable Energy*, **68**:46–50, 2014.

On the Influence of Coriolis Forces on the Structure and Evolution of Wind-Turbine Wakes

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Key words: Wind-turbine wakes, Wind farms, Coriolis forces, Wake meandering

In this study, large-eddy simulation is combined with a turbine model to investigate the effect of Coriolis forces on the structure and evolution of wind-turbine wakes under the stably-stratified condition. In order to isolate the Coriolis effect on the turbulent wake flow, two set of simulations are performed. In the first set of simulations, atmospheric boundary layer (ABL) flow is driven by the geostrophic forces including the effect of Earth's rotation, while in the second case, the ABL flow is driven by a constant pressure gradient forcing. Both cases have the same stability (i.e., Obukhov length) and boundary-layer depth. It should be noted that considering the Coriolis forces in the governing equations allows investigating how the wind direction veer inside the ABL affects the evolution of wind-turbine wakes, which is not possible in the unidirectional boundary layer flow resulting from an imposed pressure gradient.

The simulation results show that the Coriolis forces significantly affect the spatial distribution of the mean velocity deficit and turbulence statistics in the wake region. In particular, it is found that the Coriolis effect, responsible for the wind direction veer, has important lateral wake stretching effects, which in turn significantly impacts the wake recovery and wake meandering characteristics downwind of the turbines. It is also shown that inside a wind farm, lateral stretching of the wake has a significant effect on the performance of the waked turbines. Specifically, for the two cases with the same stability and turbulence level, the power extracted from the wind farm is higher under the case with larger wind direction veer in the incoming wind.

Inspired by the obtained results, a simple wake model is developed to account for the stretching of the wake downwind of the turbines. The new model is based on mass and momentum conservation and considering a multivariate Gaussian distribution for the velocity deficit which allows to account for the different lateral and vertical growth rates, as well as the skewed structure of the wake.

Importance of boundary layer height and Coriolis forces for energy extraction in large wind farms

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Key words: Boundary layer height, Wind farm, Conventionally neutral boundary layer, Large-eddy simulation

Studies on the interaction between large wind farms and the atmospheric boundary layer usually assume that the turbines fall within the boundary layer's inner region, and that they are unaffected by the scales of the outer layer. For typical wind-turbine dimensions (e.g., hub height and rotor diameter of 100 m), this working hypothesis is a good approximation in truly neutral or convective boundary layers, where the boundary layer often extends up to several kilometres. However, there are other atmospheric conditions that yield much lower boundary layer heights, e.g., stable or conventionally neutral conditions. In this study, we consider the conventionally neutral boundary layer (CNBL), the height of which is often limited by a stable inversion layer or capping inversion. In case of a low inversion layer, the wind turbines will reach into the outer region of the boundary layer and the farm will be affected by external effects such as Coriolis forces and the boundary layer height.

The impact of the boundary layer height on large wind farms is investigated by means of large-eddy simulations (LES), for which the in-house research code SP-Wind is used (cf., e.g. Calaf et al. [1]). The recently developed concurrent-precursor method [2] circumvents the periodic boundary conditions inherent to spectral discretizations, thereby allowing the study of entrance effects and spatially developing internal boundary layers in finite wind farms. The undisturbed boundary layer height upstream of the wind farm is varied by considering inversion layers at different altitudes with corresponding inversion strengths, such that the resulting CNBL is in equilibrium.

It is shown that the height of the boundary layer has a direct impact on the wind-farm power extraction. For example, in the fully developed wind farm CNBL regime, the difference in power extraction in a boundary layer of approx. 700 m and 1100 m is almost 25 %. This difference mainly originates from the work done by the driving pressure gradient, while entrainment of kinetic energy from the free atmosphere does not play a significant role. Furthermore, in finite wind farms, the growth of an internal boundary layer due to the slowing down of the incoming flow is clearly visible. As the Coriolis forces are linearly dependent on the velocity magnitude, slowing down the flow will change its direction throughout the farm. For a wind farm consisting of 20 rows, we observe a streamwise wind veer on the order of 5° near the end of the farm. This direction change is large enough to deflect the turbine wakes away from the downstream turbine so that it is only partially hit by the wake, resulting in an average flow acceleration and an increased energy extraction in the last rows of the farm.

[1] M. Calaf, C. Meneveau and J. Meyers, "Large eddy simulation of fully developed wind-turbine array boundary layers," Phys. Fluids **22**, 015110 (2010).

[2] R. J. A. M. Stevens, J. Graham and C. Meneveau, "A concurrent precursor inflow method for large eddy simulations and applications to finite length wind farms," Renewable Energy **68**, 46-50 (2014).

Large Scale Meandering in Wind Farms.

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Key words: Wind farms, Wake Interaction, Meandering, LES, Actuator Line

The Dynamic Wake Meandering model(DWM) by Larsen et al. [5] is considered state of the art for modelling the dynamic nature of the wake behind a wind turbine. DWM assumes a quasi-steady wake deficit being transported downstream as a passive tracer by large atmospheric scales. DWM is also employed to mimic the highly complex and dynamic wake interaction within large wind farms by superposing multiple turbine wakes. DWM has shown good agreement with power production and loads for the first and fifth turbine in a wake situation at the Dutch wind farm Egmond aan Zee, see Larsen et al. [6]. However, a recent study on the same wind farm showed how DWM fails at capturing certain aspects of wake meandering deep inside large wind farms, see Churchfield et al. [3].

A number of studies have shown how the presence of turbines introduce additional large scale in the wake, which could assist in describing the short comings of DWM. Chamorro et al. [2] related the power production and strain on a full scale turbine to three different regions of the lengths scales, which was not only governed by atmospheric length scales. Iungo et al. [4] performed stability analysis and matched with experimental data to show how low frequencies arise due to the instability of the hub vortex. Similarly, Okulov et al. [7] experimentally investigated the far wake behind a rotor and found Strouhal numbers of 0.23 stemming from the rotating helical vortex core. Finally, numerical investigations by Andersen et al. [1] found low frequencies to be inherent in the flow inside a an infinitely large wind farm, even in the absence of atmospheric turbulence.

The basic hypothesis of DWM is tested through several Actuator Line and Large Eddy Simulations(LES) of large wind farms. The simulations were performed in EllipSys3D to investigate the interaction between stochastically generated turbulence and the inherent dynamics of the wake behind wind turbines in order to elucidate on the origin of meandering in wind farms. Preliminary analysis of the simulations clearly show how meandering is indeed inherent to the flow in large wind farms. The final analysis further examines effects of turbulence on the wake structures.

[1] Andersen, S. J., Sørensen, J. N., and Mikkelsen, R. F. Simulation of the inherent turbulence and wake interaction inside an infinitely long row of wind turbines. *Journal of Turbulence 14*, 4 (2013), 1–24.

[2] Chamorro, L. P., Lee, S.-J., Olsen, D., Milliren, C., Marr, J., Arndt, R., and Sotiropoulos, F. Turbulence effects on a full-scale 2.5MW horizontal-axis wind turbine under neutrally stratified conditions. *Wind Energy 18*, 2 (2015), 339–349.

[3] Churchfield, M. J., Lee, S., Moriarty, P. J., Hao, Y., Lackner, M. A., Barthelmie, R., Lundquist, J. K., and Oxley, G. A Comparison of the Dynamic Wake Meandering Model, Large-Eddy Simulation, and Field Data at the Egmond aan Zee Offshore Wind Plant.

[4] Iungo, G. V., Viola, F., Camarri, S., Porté-Agel, F., and Gallaire, F. Linear stability analysis of wind turbine wakes performed on wind tunnel measurements. *Journal of Fluid Mechanics 737* (12 2013), 499–526.

[5] Larsen, G. C., Madsen, H. A., Bingöl, F., Mann, J., Ott, S., Sørensen, J. N., Okulov, V., Troldborg, N., Nielsen, M., Thomsen, K., Larsen, T. J., and Mikkelsen, R. Dynamic wake meandering modeling. Tech. Rep. R-1607(EN), Risø-DTU, Roskilde, Denmark, 2007.

[6] Larsen, T., Aagaard Madsen, H., Larsen, G., and Hansen, K. Validation of the dynamic wake meander model for loads and power production in the egmond aan zee wind farm. *Wind Energy* (2012).

[7] Okulov, V. L., Naumov, I. V., Mikkelsen, R. F., Kabardin, I. K., and Sørensen, J. N. A regular strouhal number for large-scale instability in the far wake of a rotor. *Journal of Fluid Mechanics null* (5 2014), 369–380.

Wavenumber-frequency spectra in the logarithmic layer of neutral atmospheric boundary layers

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Key words: atmospheric boundary layers, wall-bounded turbulence, space-time correlations, turbulence modeling

We study space-time correlations of streamwise velocity fluctuations in neutral atmospheric boundary layers by means of large-eddy simulations of rough-wall turbulence. Large-eddy simulations are well suited for such investigations because they provide a full space-time record of the flow at a reasonable computational cost. For our purposes studying the wavenumber-frequency spectrum, which is related to the two-point–two-time covariance by Fourier transform, turns out to be particularly useful. We find that the frequency distributions exhibit a Doppler shift, which is a consequence of mean flow advection, as well as a considerable Doppler broadening, consistent with the Kraichnan-Tennekes random sweeping hypothesis [1, 2]. For wall-bounded turbulence, both of these effects vary with the wall distance and are closely related to the logarithmic behavior of the mean velocity profile and the velocity fluctuation profiles.

We incorporate these observations into a simple analytical model for the wavenumber-frequency spectrum based on an advection equation featuring advection of the small-scale velocity fluctuations with a mean and a large-scale random-sweeping velocity [3]. The model is found to be in good agreement with the LES data. Besides presenting the model and comparisons with LES data, we will discuss potential applications of the model to wind energy conversion, such as quantifying the spatio-temporal structure of fluctuations in wind fields.

Acknowledgements Supported by DFG grant WI 3544/2-1 and WI 3544/3-1, 'Fellowships for Young Energy Scientists' (YES!) of FOM, and the US National Science Foundation grant IIA 1243482.

[1] R. H. Kraichnan. Kolmogorov's hypothesis and Eulerian turbulence theory. *Phys. Fluids*, 7:1723–1734, 1964.

[2] H. Tennekes. Eulerian and Lagrangian time microscales in isotropic turbulence. *J. Fluid Mech.*, 67:561–567, 1975.

[3] M. Wilczek, R.J.A.M. Stevens, and C. Meneveau. Spatio-temporal spectra in the logarithmic layer of wall turbulence: large-eddy simulations and simple models. *J. Fluid Mech.*, 769:R1 2015.

Experimental Investigation of Effects of Tip Injection on the Performance of Two Interacting Wind Turbines

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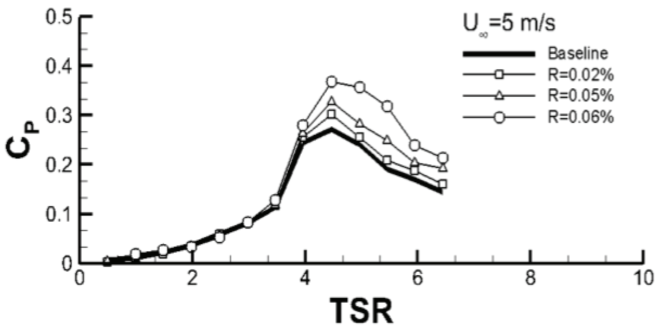
Key words: Wake Interaction, Tip Injection, Flow Control, Wind farms

In wind farms, most wind turbines operate within the aerodynamic wake of upstream turbines. As Adaramola and Krogstad (2011) showed experimentally, the power loss of a downstream turbine can reach up to 46% compared to an unobstructed single turbine operating at its designed condition [1]. Tip injection is known as an active way to control tip vortices, which also have significant role in the characteristics of wind turbine wake. Effects of tip injection on a single model wind turbine has been recently investigated by our research group. Figure 1a presents the effects of air injection with varying injected mass flow rates from blade tips of a single model wind turbine on its power coefficient variations with Tip Speed Ratio (TSR). Results provide convincing evidence that tip injection has significant effects on the power coefficient in comparison with the no injection data, especially at TSR values that are higher than the maximum power coefficient TSR value [2]. Tip injection not only affects the loads on the turbine but it has significant effects on its wake characteristics as well, as shown in Abdulrahim et al (2015)[3]. Current study aims to experimentally investigate the effects of tip injection on the performance of two interacting horizontal axis wind turbines placed at the exit of an open jet wind tunnel that has an exit diameter of 1.7 m. The turbines are three bladed with 0.95 m diameter. Blades are non-linearly twisted and tapered with NREL S826 profiles. Air will be injected from the blade tips of the upstream turbine while the blades are rotating at specified TSR values. The effects of tip injection from the upstream turbine on the torque and thrust characteristics of the downstream turbine will be measured using the data gathered from a torque meter and a load cell implemented in the design of the downstream turbine. Figure 1b shows a picture of two model wind turbines placed at the exit of METUWIND open jet wind tunnel.



(a)

(b)

Figure 1- (a) Effect of air injection from blade tips of a single wind turbine on its power coefficient variations with Tip Speed Ratio (TSR) [2], (b) Two horizontal axis wind turbines placed at the exit of the open jet wind tunnel.

[1] M.S. Adaramola, P.-Å. Krogstad, "Experimental investigation of wake effects on wind turbine performance", Renewable Energy 36 (2011) 2078-2086.

[2] E. Anik, A. Abdulrahim, Y. Ostovan, B. Mercan, O. Uzol, "Active control of the tip vortex: an experimental investigation on the performance characteristics of a model turbine", The Science of Making Torque from Wind (TORQUE2014), Copenhagen, Denmark 17-20 June, 2014.

[3] A. Abdulrahim, E. Anik, O. Uzol, "Experimental investigation of the wake flow field of a model wind turbine rotor with tip injetion", AIAA SciTech, 33rd Wind Energy Symposium, Kissimmee, Florida, 5-7 January, 2015.

The Simulation of Wind Farm Wakes with Mesoscale Models

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Key words: Wind farm paramtrisation, Mesoscale Model, Satellite images

With an increasing density of large wind farms in the North-Sea area, a better understanding of the interaction between individual wind farms is required. Mesoscale models simulate the atmospheric flow over large areas, which can cover the whole North Sea. This makes them suitable to model wakes behind large wind farms and study the influence of the wind farms to the atmosphere. However, the grid-mesh of the model is in the order of kilometres. Processes smaller than the grid-size remain unresolved and have to be accounted for in parametrisations. The effects of wind turbines to the flow is one example of an unresolved process.

The Weather Research and Forecast model [1] is released, from version 3.4 onwards, with a wind farm parametrisation (WRF-WF) [2]. The WRF-WF parametrization applies a local drag force to the grid-cell averaged Reynold Averaged Navier-Stokes (RANS) equations. Additionally, it adds a source term to the model's Turbulence Kinetic Energy (TKE) equation. At DTU Wind Energy a different approach has been developed [3]. In the Explicit Wake Parametrisation (EWP), we apply a grid-cell averaged drag force to the RANS equation, in which the volume averaged force accounts for the sub-grid scale turbine induced wake expansion. The additional TKE comes from the (vertical) shear (in mean horizontal velocity) production term of the Planetary Boundary Layer scheme, whereas the local turbine induced turbulence is on the grid-cell average neglected. The EWP approach has been implemented is the WRF model and compared to the WRF-WF parametrisation. The differences in the TKE budget between the WRF-WF and the EWP scheme, as well as the impact on relevant variables in the boundary layer will be presented.

For the European Energy Research Alliance - Design Tool for Offshore Wind Farm Cluster (EERA-DTOC) project, the EWP approach has been compared to Synthetic Aperture Radar (SAR) images. In the SAR images a flow reduction of several tens of kilometres behind offshore wind farms in the North-Sea can be recognised. The images show, furthermore, how large scale dynamics influence the wake propagation. For the selected cases, the extensions of the wind farm wakes, as well as their shape could be captured with the mesoscale model with wind farm parametrisation.

[1] Skamarock, W., Klemp J., Dudhia J., Gill, D., Barker, D., Duda M., Huang X., Wang W., and Powers, J,. A Description of the Advanced Research WRF Version 3. *NCAR Technical note*, 2008.

[2] Fitch, A., Olson, J., Lundquist, J., Dudhia, J., Gupta, A., Michalakes J., and Barstad, I.. Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model. *Mon. Weather Rev.*, 140, 3017–3038, 2012.

[3] Volker, P.J.H. "Wake Effects of Large Offshore Wind Farms - a study of the Mesoscale Atmosphere," DTU Wind Energy, 132 (2014).

Impact of wind farms on the North Sea climate

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Key words: Wind farms, North Sea, Climate

Offshore wind deployment is foreseen to expand dramatically in the coming years. The strong expansion of offshore wind parks is likely to affect the regional climatology of the coastal areas surrounding the Atlantic, North Sea and Baltic Sea. However, the impact of these parks on the regional scale remains unclear as little validation has been performed on them. In this study, a framework for validating a wind farm parameterisation against LES data is developped using an idealised version of the COSMO-CLM regional climate model. Two neutral flows in the presence of wind farms are simulated, one with and one without Coriolis, and both are validated against wind farm LES data. Root mean square errors in wind speed of 3 % and 10% are found for the non Coriolis and Coriolis cases respectively. In a second step, the wind farm parameterisation is implemented in a non idealised version of COSMO-CLM over the North Sea at a kilometer scale resolution. The wind farm enhance the turbulent kinetic energy above and within the rotor. This has an impact on the evaporation at the surface, and low level cloud cover. Futhermore, wind farms change the shape of the Ekman spiral. This has consequences on the height of the planetary boundary layer, which may affect power production.

[1] U Blahak, B Goretzki, and J Meis. A simple parameterization of drag forces induced by large wind farms for numerical weather prediction models. European Wind Energy Conference and Exhibition 2010, EWEC 2010, 6(1):4577–4585, 2010.

[2] Anna C. Fitch, Joseph B. Olson, J. K. Lundquist, J. Dudhia, A. K. Gupta, J. Michalakes, and I. Barstad. Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model. Monthly Weather Review, 140(9):3017–3038, September 2012.

[3] M. Calaf, C. Meneveau, and J. Meyers. Large eddy simulation study of fully developed wind-turbine array boundary layers. Physics of Fluids, 22(1):015110, 2010.

An LES study of a large wind farm during a realistic (CASES99) diurnal cycle

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Keywords: Large Eddy Simulation, wind farm, wind turbine, wake.

With the expanding role of wind energy to help satisfy the energy demands around the world, wind farms are covering increasingly larger surfaces to the point where interaction between the wind farms and the atmospheric boundary layer (ABL) might have significant implications. Past studies have shown how the presence of wind farms alters the land-atmosphere connection, with changes in the surface momentum and energy fluxes. Also by staggering large arrays of wind turbines there exists the potential to alter the local fluid dynamics rendering the initial wind resources assessment no longer representative.

In an attempt to comprehensively answer these questions, Large Eddy Simulation (LES) of a realistic diurnal cycle with an embedded wind farm are performed. Simulations are forced by a constant geostrophic forcing with time-varying surface boundary conditions derived from a selected period of the CASES-99 field experiment. Wind turbines are represented using the actuator disk with rotation model including yaw correction such that wind turbines self-orient with the time changing wind conditions. LES is performed using a pseudo-spectral approach implying that an infinitely large wind farm is simulated.

Comparison of simulations with and without wind farms shows clear differences in vertical profiles of horizontal velocity magnitude and direction, turbulent kinetic energy, momentum and scalar fluxes. The effect of wind farms on the characteristics of the low-level jet, depth of the stable boundary layer, formation and growth of the convective boundary layer (CBL) and scalar fluxes at the surface are shown. Results illustrating differences in power available for extraction during the course of the diurnal cycle will be presented.

Effect of topography on wind turbine power fluctuations and blade loads

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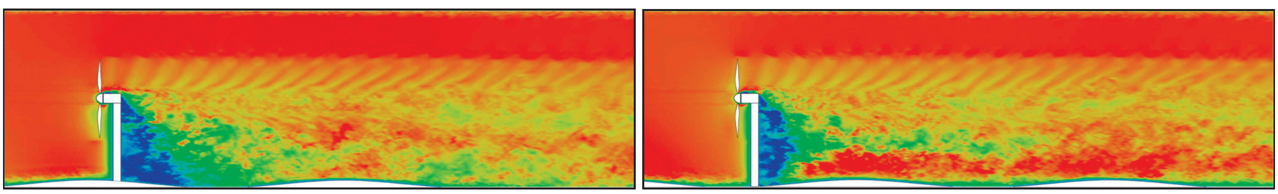
Key words: Wind turbine, Topography, Power Fluctuations, Loads

The atmospheric conditions and the local topography of the region are elements that affects the aerodynamic loads and, as a consequence, the power production of onshore wind turbines. While the effect of the atmospheric boundary layer had been widely studied, less attention has been given to the effect of the topography on the aerodynamic of the wind turbines. In order to address how the wall topography affects the flow, Large Eddy Simulations are carried out. Four simulations have been performed varying the height of the waviness and the position of the turbine within one wavelength. The wavelength, λ, is $1.7D$ while the height is $a/D = 0.05$ and $a/D = 0.10$, where a is the amplitude of the wave and D is the wind turbine rotor diameter. For each case, the turbine is positioned on the crest and trough of the wavy wall. A simulation with a flat wall was also carried out as reference case. The numerical code is based on a finite difference scheme with a fractional step and a Runge-Kutta, providing a second order accuracy in space and time. It combines the immersed boundary method (IBM) to model the tower, nacelle, and the topography with the actuator line method (ALM) to represent the aerodynamic loads of the blades.

At $x/D = 1$ (where x is the distance from the rotor disk), when the turbine is placed on the crest, the velocity on the lower part of the turbine rotor disk is smaller than that relative to the smooth wall reference case. The opposite is observed when the turbine is placed on the center of the cavity. This is due to the pressure field induced by the wavy wall and its interaction with that caused by the blockage of the turbine. For $x/D > 3$, the velocity profiles almost overlap within the rotor disk height. The tower induces separation of the flow. When the turbine is placed on the crest, the recirculation length is 2.5 times larger than that relative to the smooth wall. The topography induces an upward shift in the vertical direction of the maximum turbulent kinetic energy, which becomes closer to the lower part of the rotor disk. While the velocity profiles collapse at $x/D = 3$, regardless of the topography, the turbulent kinetic energy depends significantly on the position of the turbine within the wavelength. By increasing the amplitude of the wavelength from $0.05D$ to $0.1D$, the turbulent kinetic energy is about 80% larger at the lower tip of the disk. This may induce larger fluctuations of loads on the downstream turbines.

The numerical simulations were performed on XSEDE TACC under Grant No. CTS070066. This work was supported by the National Science Foundation, grant number IIA-1243482 (the WINDINSPIRE project).



Streamwise velocity colormap for the wind turbine located at the crest and trough of the wavy wall topography

Structural Impact of Different Low Level Jet Types over Wind Turbines in West Texas

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Key words: Wind turbine, Low Level Jet, LLJ

Low Level Jets (LLJs) are defined as regions of relatively strong winds in the lower part of the atmosphere. They are a common feature over the Great Plains in the United States. It has been reported that 75 % of LLJs in the Great Plains occur at night and with seasonal patterns, affecting significantly the wind energy production. Present results have corroborated some of the LLJ known characteristics. LLJ are effected by the stable stratification in the lower atmosphere and the inversion of potential temperature that occurs mainly at night in the Great Plains. This paper is focused on the determination of the static/dynamic impact that different types of LLJs (according to strength and height) in West Texas have over wind turbines. High-frequency (50Hz) observational data from the 200-m tower data (Reese, Texas) have been input as in low conditions into the NREL FAST code in order to evaluate the structural impacts of LLJ's on a typical wind turbine. Due to the cubic relation with velocity, the potential for power is increased more than two times at the hub height of current utility wind turbines. It has been observed that during a LLJ event the level of turbulence intensities and TKE are significantly much lower than those during unstable conditions; as a result, cyclical aerodynamic loads on turbine blades are different. Low-frequency oscillations prevail in stable conditions with production of LLJ, as opposed to high-frequency oscillations more prevalent in unstable conditions. The turbulent kinetic energy is lower in LLJ but the energy concentrates in particular frequencies that can stress the turbine. And from the point of view of the wind turbine variables, we have detected frequencies that can be correlated with those from the incoming wind.

[1] AWEA Data Services. U.S. Wind Industry Third Quarter 2014 Market Report. Technical report, AWEA (2014).

[2] William D Bonner, "Climatology of the Low Level Jet," Monthly Weather Review, 96(12):833{850, (December 1968).

[3] W. Choi, I. C. Faloona, M. McKay, A. H. Goldstein, and B. Baker, "Estimating the atmospheric boundary layer height over sloped, forested terrain from surface spectral analysis during BEARPEX," Atmospheric Chemistry and Physics, 11:6837 (2011).

[4] N.D. Kelley, "Turbulence-Turbine Interaction: The Basis for the Development of the TurbSim Stochastic Simulator," Technical report, National Renewable Energy Laboratory, Golden, CO, USA (2011).

[5] NREL National Wind Technology Center. NWTC Information Portal (FAST v8). https://nwtc.nrel.gov/FAST8.

[6] David J. Stensrud, "Importance of Low-Level Jets to Climate: A Review. Journal of Climate", 9:1698{1711 (August 1996).

[7] West Texas Mesonet. 200 m Met Tower. http://www.depts.ttu.edu/nwi/facilities/200-m-tower.php

Available Active Power Estimation for Offshore Wind Power Plants

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Key words: Available Power, Down-regulation, Real-time Wake Modelling

The modern offshore wind power plants are down-regulated (or curtailed) more frequently due to increasing shares in wind, making available (or possible) power estimation even more crucial. Currently, there is no clear way to determine exactly the available power of a down-regulated wind farm even though the modern wind turbines have a SCADA signal called possible power. The sum of those individual signals is a clear over-estimation of the available power of a down-regulated wind farm simply because the wind speed is higher at the downstream turbine location(s) due to the decrease in wake losses under curtailment. This paper describes an industrially applicable method for the real-time estimation of the available power of a wind farm developed in the frame of PossPOW project (see posspow.dtu.dk).

To develop the real-time (1 Hz) wind farm scale available power signal, the free wind speed at the upstream turbine locations has to be estimated and input to the wake model, calibrated for the same resolution, to obtain the corrected downstream wind. In this paper, the details of the available power algorithm are presented together with the validation cases prepared using a set of wind farm scale experiments in Horns-Rev offshore wind farm.

To estimate the wind speed at turbine locations, a new approach which takes power, pitch angle, and rotational speed as inputs is developed and validated during both down-regulation and normal operation using 1 Hz met mast and SCADA data from the Horns Rev, Lillgrund and Thanet offshore wind farms, together with NREL 5MW simulations.

The wind speeds of the upstream turbines should be read by the wake model to estimate the velocity deficit for nominal operation and calculate the possible power of the wind farm. However, most of the robust wake models are tuned for 10-min averaged data. Therefore, the GCLarsen wake model is re-calibrated for single wake cases and then implemented to the farm scale considering the time delay and the local turbulence. The preliminary results on Thanet indicate that the wake velocity inside the wind farm can be estimated with a maximum 10-min average error of 12% using the re-calibrated model on 1-sec dataset. When applied during the nominal operation, the algorithm clearly provides a real-time wind farm power curve which can then be fed into the control system.

The test and validation of the algorithm is rather challenging since there is no actual measure of the available power for wind farm scale. However, we can benefit from the similarity in power production between the neighbouring rows in a simple layout like Horns Rev wind farm. The idea behind the validation and the experimental setup is described in another paper in the proceedings, see Giebel et al. The first results of the experiment indicate a significant improvement in the available active power signal calculated by the described algorithm compared to the current approach. The preliminary verification studies and uncertainty analysis of both approaches is performed based on the experimental results.

[1] G. C Larsen and P. E. Réthoré *A simple stationary semi-analytical wake model* (Technical Report Risø, 2009).

Dynamic mode decomposition applied to large-eddy simulations of wind farms

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Key words: Wind farms, Large eddy simulation, Proper orthogonal decomposition, Dynamic mode decomposition

Power generation by wind farms is growing rapidly in response to the increasing demand for carbon neutral power. A better understanding of the dynamics of wind turbine wakes and their interactions is necessary for designing more efficient wind farms. In this work dynamic mode decomposition (DMD) is used to analyze large eddy simulations (LES) of a wind turbine in the atmospheric boundary layer. DMD is similar to proper orthogonal decomposition (POD) in that it decomposes the flow into discrete structures, which can be used to build reduced order models of the data. Unlike POD modes, which are spatially orthogonal, the DMD modes are independent in frequency. Simulations of the flow using only a subset of the DMD modes can be generated, permitting an examination of the most important flow interactions absent unimportant structures.

Analysis of a single-turbine LES shows that the first DMD mode captures the average convection velocity, including flow deflection around the turbine rotor. A reduced order model of the system using 500 out of 2800 DMD modes captures the large scale dynamics present in the original simulation data. Sparsity promoting dynamic mode decomposition (SPDMD) uses a regularized convex optimization problem to identify those DMD modes whose temporal behavior most strongly influences the system. In contrast to DMD analysis, SPDMD analysis retaining only 106 out of 2800 DMD modes is sufficient to accurately recover the behavior of the turbine wake. When the SPDMD analysis of single turbine simulations is restricted to a single mode, SPDMD identifies the time-averaged mean velocity field which is dominated by the turbine-induced wake and atmospheric boundary layer. SPDMD provides information about a time-varying mean which is otherwise not available using the standard DMD or POD analyses. We will also explore the benefit of SPDMD analysis in multiple turbine arrays.

This research is supported by NSF (grant IIA-1243482, WINDINSPIRE and SEP 1230788).

[1] P. J. Schmid, “Dynamic mode decomposition of numerical and experimental data," The Journal of Fluid Mechanics **656**, (2010).

[2] C. VerHulst and C. Meneveau, “Large eddy simulation study of the kinetic energy entrainment by energetic turbulent flow structures in large wind farms," Physics of Fluids **26**, (2014).

[3] M. R. Jovanović and P. J. Schmid and J. W. Nichols, “Sparsity-promoting dynamic mode decomposition," Physics of Fluids **26**, (2014).

Data-driven Reduced Order Model for prediction of wind turbine wakes

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Key words: Reduced order model, dynamic mode decomposition, Kalman filter, wind turbine wakes

Numerical simulations carried out over the last decades have achieved detailed characterizations of the wake flow produced by a wind turbine [1]. However, the boundary layer over the turbine blades is typically not resolved, and the forcing produced by the turbine loads on the atmospheric boundary layer is enforced through different models, such as the actuator disc and actuator line model. The computational cost of high fidelity simulations remains far too high, which makes them inapplicable for operational purposes. As a consequence, simple analytical wake models are still considered as standard frameworks for prediction of power harvesting from a wind power plant and for siting new wind farms, even if they are characterized by a limited accuracy.

In this work a new methodology for prediction of wind turbine wakes and performance is proposed. This tool is characterized by a computational cost of at least two orders of magnitude smaller than that for classical actuator disc LES simulations, but it still enables to achieve a comparable accuracy. Specifically, a Reduced Order Model (ROM) is evaluated by means of Dynamic Mode Decomposition (DMD) [2]. By processing a limited set of wake velocity measurements, either experimental or numerical data, it is possible to select a small number of coherent realizations of the wake flow that optimally represent the dynamic evolution of wind turbine wakes. The formulation of the ROM is performed accordingly to the objective of the investigation. Indeed, the ROM can be obtained as a function of different criteria, such as reconstruction of downstream turbulent fluctuations of the wind field, added fatigue loads on downstream turbines, estimation of the residual power for waked turbines, among others. This broad range of available options for producing an optimal ROM increases largely the performance of this tool compared to classical methods based only on energy content criterion, such as for the Proper Orthogonal Decomposition.

The small computational time of the ROM, and high accuracy are achieved by selecting a reasonable small subspace dimension, thus a limited number of significant DMD modes. The ROM is then embedded within a Kalman Filter in order to produce a time-marching algorithm for prediction of wind turbine wake flows and performance. This data-driven algorithm also enables data assimilation of new measurements, simultaneously to the wake predictions. This procedure leads to an improved accuracy and a dynamic update of the ROM in case new coherent dynamics are observed from new available data. In this work the data-driven ROM is calibrated on high fidelity LES data of a wind turbine wake. A good level of accuracy is obtained for dynamic predictions of the wake flow through the ROM. This novel tool is particularly suitable for real time applications, control and optimization of large wind farms. (This work is partially founded by the National Science Foundation, grant number IIA-1243482, the WINDINSPIRE project).

[1] L. A. Martinez-Tossas, M. J. Churchfield and S. Leonardi, "Large eddy simulations of the flow past wind turbines: actuator line and disk modeling," Wind Energy (2014).

[2] P. J. Schmid, "Dynamic mode decomposition of numerical and experimental data," J. Fluid Mech. **656**, 5-28 (2010).

Statistical Modeling of Wind Farm Power Production: A Study of Predictive Accuracy for Multiple Wind Farms

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Key words: Operational Wind Farms, Statistical Analysis, Farm Power Prediction, Model Comparison

Existing fluid dynamics-based models are limited in their ability to predict the behavior of real wind farms. This is especially true among wind farms that do not have regularly-spaced turbines aligned in consecutive rows, as much of the early research has focused on row-aligned farms [1]. Many models can accurately capture the turbine wake interactions within a farm, but, in a real, operational wind farm, the wakes are dependent on other unknown variables that are difficult to properly measure and assess. This makes it difficult to accurately assess the power production of an entire wind farm in the real world using only wake-decay models. For example, measured data at one meteorological tower in or near a farm is not representative of the wind seen elsewhere in the farm, especially for very large wind turbine arrays. In many cases, it is also difficult to assess the turbulence level present in the upstream wind field.

Before a wind farm is built, a meteorological tower is typically installed and plans are made for farm placement and turbine layout based on these single-point measurements. It is often a highly simplified process [2]. It is therefore beneficial to be able to improve our understanding of wind farm planning in this context. We propose statistical methods to better predict the performance of a wind farm for planning purposes. Statistical models can intrinsically capture the complexities present in a wind farm without having to model them explicitly. We train models on actual data from two different operational wind farms, and we use variables including meteorological tower measurements and information on the turbine placement in relation to any upstream turbines in the farm to predict the total power production of the wind farm.

We analyze the performance of several different types of statistical models and compare the use of different variable combinations, including the application of models that use information regarding the velocity wake deficit present at each turbine, which is calculated from a coupled-wake boundary layer model [3]. Here, we present results of our models' predictive accuracy, both for the same farm that the models were trained on, and when applied to the second farm that is used as an independent test case. The results vary by wind direction, and we present a comparison of the accuracy as a function of wind direction and show the effect that turbine layout has under various wind conditions and for the two different farms.

[1] Sten Frandsen, Rebecca Barthelmie, Sara Pryor, Ole Rathmann, Søren Larsen, Jørgen Højstrup, and Morten Thøgersen, "Analytical modelling of wind speed deficit in large offshore wind farms," Wind Energy **9**, 39-53 (2006).

[2] Andrew Kusiak and Zhe Song, "Design of wind farm layout for maximum wind energy capture," Renewable Energy **35**:3, 685-694 (2010).

[3] Richard J. A. M. Stevens, Dennice F. Gayme, and Charles Meneveau, "Coupled wake boundary layer model of wind-farms," Submitted to J. Renewable and Sustainable Energy (2014).

Turbulent inflow precursor method with time-varying direction for large eddy simulations and applications to wind farms

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Key words: Wind farms, Large eddy simulation

In large wind farms, the turbines exhibit complex interactions with the highly turbulent atmospheric boundary layer (ABL). Moreover, wake interactions between individual turbines lead to a significant reduction in power extracted by downstream rows. In recent years, the use of large eddy simulations (LES) has been an important contributor to gaining insights in the complex flow physics involved. In LES, the large energy-containing turbulent flow fluctuations, which are particularly relevant for wind farm ABL interaction, are spatially and temporally resolved. However, a major challenge in turbulence-resolving flow simulations is the generation of unsteady and coherent turbulent inflow conditions. Precursor methods have proven to be reliable inflow generators but are limited in applicability and flexibility, especially when attempting to couple boundary layer dynamics with large-scale temporal variations in the direction of the inflow.

In this work, we propose a methodology which is capable of providing fully developed turbulent inflow for time-varying mean flow directions. The method is a generalization of a concurrent precursor inflow technique, [1] in which a fully-developed boundary layer simulation that uses periodic boundary conditions is dynamically rotated with the large scale wind direction that drives the simulation in the domain of interest.

Simulations are performed using our in-house research code SP-Wind developed at KU Leuven (cfr., e.g. Refs [2, 3]). The filtered Navier-Stokes equations are solved using a mixed pseudo-spectral / finite-difference discretization scheme combined with a fourth order Runge Kutta time integration method. Inflow conditions are specified through the use of a fringe region technique. Wind turbines are represented with a classical actuator disk model.

First, the importance of high quality inflow turbulence is evidenced based on the simulation of a high-Reynolds number turbulent boundary layer, in which inflow conditions are generated with our precursor method as well as synthetic inflow methods. The proposed inflow precursor method is subsequently applied to a LES study of boundary layer flow through the Horns Rev wind farm when subjected to a hypothetical sinusoidal variation in wind direction at the hourly scale. Time-averaged results are compared with both numerical and experimental reference data. In addition, transient flow phenomena and wind farm behavior are identified.

[1] R.J.A.M. Stevens, J. Graham and C. Meneveau "A concurrent precursor inflow method for large eddy simulations and applications to finite length wind farms," Renewable Energy **68**, 46-50 (2014).

[2] J.P. Goit and J. Meyers "Optimal control of energy extraction in wind-farm boundary layers," Journal of Fluid Mechanics **768**, 5-50 (2015).

[3] M. Calaf, C. Meneveau and J. Meyers "Large eddy simulation study of fully developed wind-turbine array boundary layers," Physics of Fluids **22**, art. no 015110 (2010).

Large-eddy Simulation of Atmospheric Boundary-layer Flow through a Wind Farm Sited on Complex Terrain

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Key words: atmospheric boundary-layer, horizontal-axis wind turbine, wind farm, wake flow, turbulence, topography, complex terrain, terrain-following coordinates

In this work, the performance of a wind farm situated on a hilly terrain is studied using large-eddy simulation and especial attention is paid to the effect of the topography on the wake flow characteristics. To this end, first, boundary-layer flow is simulated over a two-dimensional hill in order to characterize the spatial distribution of the mean velocity and the turbulence statistics. Subsequently, a simulation is performed of flow through a wind farm consisting of five horizontal-axis wind turbines sited over the same hill in an aligned layout, and the resulting flow characteristics are compared with the former case, i.e., the case without wind turbines. To assess the validity of the simulations, the results are compared with the measurements carried out by Tian et al. (2013) in the aerodynamic/atmospheric boundary layer wind tunnel of Iowa State University. The agreement between the simulation and experimental results is good in terms of mean velocity and turbulence intensity profiles at different streamwise positions. The study is also accompanied with a proper orthogonal decomposition (POD) analysis of the flow field.

Enhanced kinetic energy entrainment in wind farm wakes: LES study of a wind turbine array with tethered kites

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Key words: wind farms, power kites, large eddy simulations (LES), kinetic energy entrainment

Wake effects in wind farms are a major source of power production losses and fatigue loads on the rotors. It has been demonstrated that in large wind farms the only source of kinetic energy to balance that extracted by the turbines is the vertical transport of the free-stream flow kinetic energy from above the wind-turbine canopy [1]. In the present study, the possibility to enhance such process by introducing kites in steady flight within the wind-turbine array is studied with numerical simulations.

An aligned array of four wind turbines is simulated within the LES framework available in the computational fluid dynamics code `FLUENT` [2]. The turbines are placed in a pre-generated turbulent atmospheric boundary layer (ABL) and modelled as actuator discs with both axial and tangential inductions, to account for the wake rotation [3]. The inter-turbine spacing is six rotor diameters while a kite is suspended three diameters downwind each wind turbine, 0.25 diameters above the top-tip height. The kite is modelled as a body force on the flow, equal in magnitude and opposite in direction to the vector sum of the lift and drag forces acting on the kite.

The introduction of the kite system is found to have a significant effect on the power generated by the wind turbine array, for suboptimal operating conditions, primarily due to the enhanced kinetic energy entrainment in the lower part of the ABL (Figure 1). The simulation results, consistent with previous findings [4], clearly suggest that the applied forcing is capable of redirecting the free-stream flow and assist wake recovery. Follow-up research on kite layout strategies for large wind farms and multiple wind directions as well as an analysis of different kite flight paths (i.e. crosswind motion) in the array is suggested.

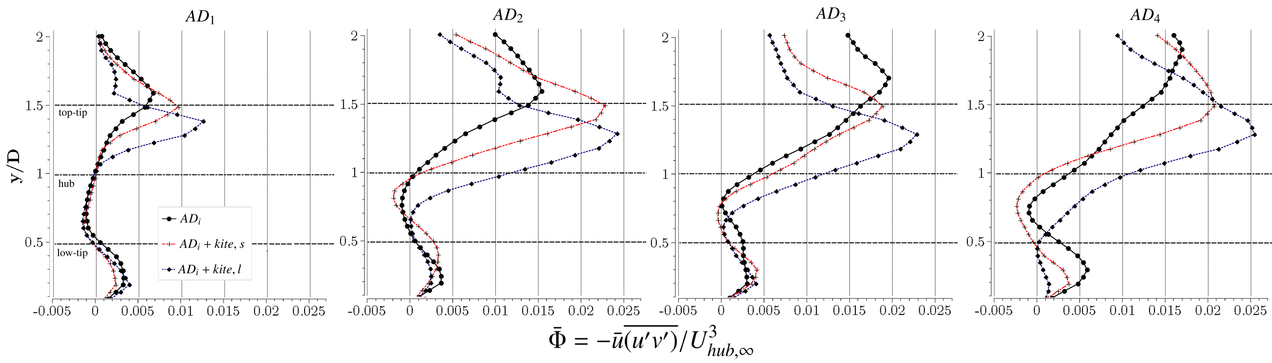

Figure 1: *The radial profiles of the normalized mean flow-kinetic energy flux, $\bar{\Phi}$, are evaluated on the horizontal x-y plane and plotted at x/D=5 downwind the actuator discs AD_i. A significant increase in the entrainment of the free-stream kinetic energy into the wind turbine wake before "AD_i" and after "AD_i+kite" the introduction of the kite is observed (black vs coloured lines). The effect of different kite surface areas, $A_{kite,s}$=$A_{AD_i}/48$ (dashed red line) and $A_{kite,l}$=$A_{AD_i}/12$ (dotted blue line), on the spatial distribution and magnitude of the mean kinetic energy flux is of particular interest.*

[1] Cal, R. B., Lebrón, J., Castillo, L., Kang, H. S., & Meneveau, C. "Experimental study of the horizontally averaged flow structure in a model wind-turbine array boundary layer." Journal of Renewable and Sustainable Energy **2.1** (2010): 013106.

[2] `FLUENT` user's guide 14.5, `http://148.204.81.206/Ansys/readme.html`, Accessed: 23/03/2015.

[3] Porté-Agel, F., Wu, Y. T., Lu, H., & Conzemius, R. J. "Large-eddy simulation of atmospheric boundary layer flow through wind turbines and wind farms." Journal of Wind Engineering and Industrial Aerodynamics **99(4)** (2011): 154-168.

[4] VerHulst, C., & Meneveau, C. "Altering Kinetic Energy Entrainment in Large Eddy Simulations of Large Wind Farms Using Unconventional Wind Turbine Actuator Forcing." Energies **8(1)** (2015): 370-386.

Large-eddy simulation of wind-farm boundary-layer transients

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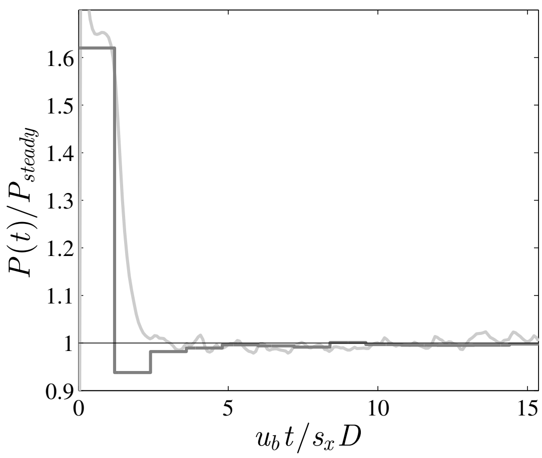
Key words: Wind farm, transient, boundary layer, start-up

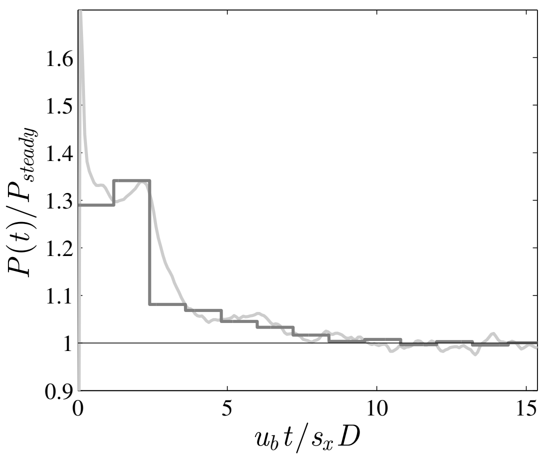
Wind turbines are often clustered together in large wind farms. The size of these farm can extend for tens of kilometers in streamwise direction, so that the wind-farm through-flow time is often more than half an hour. This causes a significant time delay before changes in control set points affect downstream turbines. For instance, when the energy extraction of down-regulated turbines is suddenly increased, this does not directly affect other turbines in the farm, so that temporarily power overshoots occur. This may be, e.g., of interest in the context of tertiary reserves, or short-term bidding the electricity market.

In the current study we investigate the wind-farm boundary layer transient when wind turbines are suddenly switched on. Simulations are performed in our in-house LES code SP-Wind [1], for a large (finite) wind farm with 14 rows of wind turbines, and different layouts. Ensemble averages are taken to reduce the statistical noise of the turbulence, by repeating the simulations using different statistically independent initial conditions. In this way, the time- and spatially resolved flow fields and stresses can be studied in a more detail.

The power evolution after a start-up is shown on figure 1, for 2 different wind farm layouts. It is found that the evolution strongly depends on layout. A simple model for this transient, based on the parabolic behaviour of the boundary layer, is also proposed.



(a)



(b)

Figure 1: Evolution of power extraction in a wind farm after sudden start-up. The light (—) and dark grey line (—) show simulated and modelled power evolution of the wind farm. (a) aligned, and (b) staggered wind farm. Time is normalized by turbine-to-turbine time.

[1] M. Calaf, C. Meneveau, and J. Meyers, "Large eddy simlulation study of fully developed wind-turbine array boundary layers," Physics of Fluids **22**, no. 1(2010).

Turbulence analysis upstream of a wind turbine: a LES approach to improve wind LIDAR technology

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Keywords: Large Eddy Simulation, Turbulent Kinetic Energy, LIDAR, wind farm, diurnal cycle.

Traditionally wind turbines learn about the incoming wind conditions by means of a wind vane and a cup anemometer. This approach presents two major limitations: 1) because the measurements are done at the nacelle, behind the rotor blades, the wind observations are perturbed inducing potential misalignment and power losses; 2) no direct information of the incoming turbulence is extracted, limiting the capacity to timely adjust the wind turbine against strong turbulent intensity events. Recent studies have explored the possibility of using wind LIDAR (Light Detection and Ranging) to overcome these limitations (Angelou et al. 2010 and Mikkelsen et al., 2014). By installing a wind LIDAR at the nacelle of a wind turbine one can learn about the incoming wind and turbulent conditions ahead of time to timely readjust the turbine settings. Yet several questions remain to be answered such as how far upstream one should measure and what is the appropriate averaging time to extract valuable information. In light of recent results showing the relevance of atmospheric stratification in wind energy applications, it is expected that different averaging times and upstream scanning distances are advised for wind LIDAR measurements.

A Large Eddy Simulation (LES) study exploring the use of wind LIDAR technology within a wind farm has been developed. The wind farm consists of an infinite array of horizontal axis wind turbines modeled using the actuator disk with rotation. The model also allows the turbines to dynamically adjust their yaw with the incoming wind vector. The flow is forced with a constant geostrophic wind and a time varying surface temperature reproducing a realistic diurnal cycle. Results will be presented showing the relevance of the averaging time for the different flow characteristics as well as the effect of different upstream scanning distances. While it is observed that within a large wind farm there are no-significant gains in power output by scanning further upstream, much can be learned about the incoming turbulence, hence allowing improved wind turbine readjustments. Time correlations with the upstream incoming turbulence have been computed through an entire diurnal cycle, and a non-dimensional analysis shows the existence of different behaviors throughout the day.

[1] Angelou, N., Mann, J., Courtney, M., and Sjöholm, M. “Doppler lidar mounted on a wind turbine nacelle–UPWIND deliverable D6. 7.1. ," Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi, (2010).

[2] T. Mikkelsen, “Lidar-based Research and Innovation at DTU Wind Energy - a Review," *In Journal of Physics:* Conference Series (Vol. 524, No. 1, p. 012007), IOP Publishing, Copenhagen, (2014).

Developing a large eddy simulation variant of the restricted nonlinear model for wall-bounded turbulent flow

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Key words: LES, RNL, reduced-order modeling, wind farms

The restricted nonlinear (RNL) model, which is derived from the Navier-Stokes equations, partitions the flow field into a streamwise-averaged mean flow and streamwise-varying perturbations while eliminating nonlinear interactions between the perturbations. Recent direct numerical simulations of the RNL model [1] have demonstrated its ability to produce self-sustaining turbulent behavior in wall-bounded shear flows. The model also accurately reproduces certain turbulence statistics, such as the turbulent mean velocity profile, at low Reynolds numbers but grows less accurate with increasing Reynolds number. However, a band-limited variant [2] of the RNL model yields improved statistics (e.g., accurate logarithmic mean velocity profiles) at moderate Reynolds numbers with a drastically reduced number of degrees of freedom. As such, the RNL model and its band-limited version are of interest for studying boundary layer flow phenomena.

One such application is the study of the fluid dynamics of wind farms in the atmospheric boundary layer. While the large eddy simulation (LES) technique has been employed successfully in recent years to study wind farm turbulence [3, 4], LES can demand significant computational resources and is thus too expensive for some studies. Significant computational savings could be realized by incorporating the RNL model into a LES framework.

Toward the goal of developing reduced-order wind farm models, we develop a LES variant of the band-limited RNL model. This involves introducing a streamwise-averaged decomposition of both a sub-grid scale model and a wall model. Early results indicate that a band-limited LES-RNL model accurately reproduces certain turbulence statistics and thus is viable as a new simulation framework for reduced-order, reduced-cost simulations of wind farms.

This work is supported by the US National Science Foundation (Nos. IGERT 0801471, ECCS-1230788, and IIA-1243482, the WINDINSPIRE project).

[1] V. L. Thomas, B. K. Lieu, M. R. Jovanović, B. F. Farrell, P. J. Ioannou, and D. F. Gayme, "Self-sustaining turbulence in a restricted nonlinear model of plane Couette flow," Phys. Fluids **26**, 105112 (2014).

[2] J. U. Bretheim, C. Meneveau, and D. F. Gayme, "Standard logarithmic mean velocity distribution in a band-limited restricted nonlinear model of turbulent flow in a half-channel," Phys. Fluids **27**, 011702 (2015).

[3] M. Calaf, C. Meneveau, and J. Meyers, "Large eddy simulation study of fully developed wind-turbine array boundary layers," Phys. Fluids **22**, 015110 (2010).

[4] H. Lu and F. Porté-Agel, "Large-eddy simulation of a very large wind farm in a stable atmospheric boundary layer," Phys. Fluids **23**, 065101 (2011).

Wind Turbine Box, the flow around a characteristic wind turbine.

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Keywords: Large Eddy Simulation, wind farm, wind turbine, wake.

Several studies analyzing the flow within a large wind farm have been presented over the past years. Because under such conditions the flow can be considered fully developed and horizontally homogeneous, the analysis has been reduced to the vertical dimension of the corresponding horizontally averaged variables. This approach has been fundamental, for example, to understand the momentum replenishment and wake recovery within large wind farms. Also, a large number of studies have focused on analyzing the flow around a single wind turbine. In them the spatial characteristics of the wind turbine wake have been well documented, generally presenting vertical and horizontal profiles throughout the wake region. Yet, the connection between the two types of analysis –i.e. single wind turbine and large wind farm, remains elusive.

This research project presents a new tool, so called "Wind Turbine Box", that allows for the direct comparison between the flow around a single wind turbine and the flow around a characteristic wind turbine immersed within a large wind farm. The Wind Turbine Box consists of a limited control volume defined around each wind turbine that is timely co-aligned with each corresponding turbine's yaw-angle. Hence it is possible to extract flow statistics around each wind turbine, regardless of whether the turbine is fully isolated or it is plunged within a large wind farm.

The Wind Turbine Box tool has been used to compare the flow around a single wind turbine and around a characteristic wind turbine of a large wind farm throughout a complete diurnal cycle. For this purpose, two independent Large Eddy Simulations (LES), one including a single wind turbine and the second one including a very large wind farm were performed. The flow was forced with a constant geostrophic wind and a time varying surface temperature extracted from a selected period of the CASES-99 field experiment. Vertical and horizontal profiles of the most relevant flow statistics will be presented, as well as the full mean kinetic and turbulent kinetic energy balances. Results will illustrate the differences in the flow dynamics developed around the single wind turbine and the wind farm immersed turbine.

Comparison of an Actuator Line Model implementation in three different Large-Eddy Simulation Codes

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Key words: Wind Turbine, Large-Eddy Simulations, Actuator Line Model

Large-Eddy Simulations (LES) has become a prominent tool for performing numerical simulations of wind farm flows [1, 2, 3]. Many groups have different implementations of actuator line and subgrid-scale (SGS) models in LES. In the present work we compare actuator line model (ALM) [4, 5] and SGS model implementations on three LES solvers. In a previous study, the codes from the Turbulence Research Group at Johns Hopkins University (JHU), LESGO, and the SOWFA package from the National Renewable Energy Laboratory (NREL) have been compared [5]. Here we extend the comparison by considering a third code, namely SP-WIND [7] from KU Leuven. Effects of SGS modeling between codes and the differences in resolving a wind turbine wake are discussed. The case chosen as a benchmark is an NREL 5 MW Reference turbine in uniform inflow of 8 m/s and a tip speed ratio (TSR) of 7.55. The domain size is 24D x 6D x 6D in size, where D is the turbine diameter. The JHU and KU Leuven solvers are based on pseudo-spectral numerics in two directions and finite difference in the third, the NREL solver is based on the OpenFOAM framework, which is a finite-volume implementation. Each simulation takes on the order of 5,000 CPU hours. Loads along the blades for the ALM are compared to predictions from Blade Element Momentum Theory (BEM). Wake velocity and Reynolds Stress profiles are presented for all cases and emphasis is given on wake breakdown predictions by the different codes. Differences in wake profiles are attributed mostly to differences in SGS model implementations and numerics. It has been seen that diffusive numerics and high SGS viscosities delay the breakdown of the wake. This work is supported by the US National Science Foundation (Nos. IGERT 0801471, ECCS-1230788, and IIA-1243483, the WINDINSPIRE project).

[1] Churchfield M J, Lee S, Moriarty P J, Martinez L A, Leonardi S, Vijayakumar G and Brasseur J G "A large-eddy simulation of wind-plant aerodynamics" *AIAA paper (2012)*

[2] Calaf M, Meneveau C and Meyers J "Large eddy simulation study of fully developed wind-turbine array boundary layers" *Physics of Fluids* **22** 2010

[3] Wu Y T and Porté-Agel F "Large-eddy simulation of wind-turbine wakes: evaluation of turbine parametrisations" *Boundary-Layer Meteorology* **146** 181–205 2012

[4] Sørensen J N and Shen W Z "Numerical modeling of wind turbine wakes" *Journal of Fluids Engineering* **124** 393–399 2002

[5] Martínez-Tossas L A, Churchfield M J and Leonardi S Large eddy simulations of the flow past wind turbines: actuator line and disk modeling *Wind Energy* 2014

[6] Martinez L A, Churchfield M J, Meneveau C "Large Eddy Simulation of wind turbine wakes: detailed comparisons of two codes focusing on effects of numerics and subgrid modeling" *Wakes* 2015

[7] Yilmaz A E and Meyers J "Numerical simulations of flow fields through conventionally controlled wind turbines and wind farms" *J. Phys.: Conf. Ser. 524 012158* (2014)

Comparison of wind turbine wake properties using actuator line and disc approaches

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Key words: Wake, Large eddy simulations, Actuator line, Actuator disc

Accurate prediction of wind turbine wakes, atmospheric boundary layer flow and their interactions provides information leading to optimal design of the wind farms. Most computational fluid dynamic (CFD) studies of wind turbine wakes are based on actuator line or actuator disc approaches as these models do not require the rotor boundary layer to be resolved. These models are less computationally demanding in comparison to the simulations where the rotor geometry is fully resolved. This makes it possible to perform simulations of entire wind farms with reduced computational resources. The needed resolution does however change substantially between the choice of method, i.e., an actuator line or an actuator disc. Therefore, it is important to quantify how well the flow physics is represented by the methods.

To address this issue, the wake of the NREL 5MW wind turbine is simulated considering the atmospheric boundary layer and moderate turbulence intensity. The numerical model is based on large eddy simulation of the Navier–Stokes equations combined with an actuator line or an actuator disc method. The simulations are performed using the EllipSys3D code. The main focus is to investigate differences between the two methods and to quantify under which circumstances they are applicable and to what accuracy.

Poster Abstracts

Stochastic characteristics of wind energy

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Key words: Flickering, Intermittency, Synchronization

In recent years the share of renewable energies such as wind power has increased constantly in power systems. The renewable sources (wind power and photovoltaics), for instance, shall account for about 20% of the gross final energy consumption by 2020 and 60% by 2050. Therefore, the statistical characteristics of the new energy sources can influence the stability of networks. A detailed modelling of the origin of the statistical behaviours is necessary to make a guideline for an optimal design of power grids.

There exist two important statistical properties for wind power: flickering and intermittency. The nonlinear flickering variability typically occurs at time scales of few seconds and high-frequency monitoring of wind power enables us to detect a transition, controlled by field size, where the output power qualitatively changes its behaviour from a flickering type to a diffusive stochastic behaviour. However, the intermittency and strong non-Gaussian behaviour in cumulative power of the wind farm, even for a country-wide installation, still survives.

The non-Gaussian statistics of the cumulative power output clearly deviates from the central limit theorem. In fact, there is an interdependency between wind turbines, which we are able to unveil using a synchronisation approach. In particular, we show by the adaption of phase synchronisation method to the performance of wind turbines the existence of the local phase synchronisation between the wind power output. Furthermore, we show that the synchronisation between wind turbines is a cause of an intermittent cumulative power output. Based on our results, methods can be proposed to eliminate the intermittent power dynamics.

[1] M. Reza Rahimi Tabar, M. Anvari, G. Lohmann, D. Heinemann, M. Wächter, P. Milan, E. Lorenz, and Joachim Peinke, "Kolmogorov spectrum of renewable wind and solar power fluctuations," Eur. Phys. J. Special Topicsl **223** (**12**), 26370 (2014).

[2] Gerald Lohmann, M. Reza Rahimi Tabar, Patrick Milan, Mehrnaz Anvari, Matthias Wächter, Elke Lorenz, Detlev Heinemann, and Joachim Peinke, "Flickering Events in Wind and Solar Power," In *EnviroInfo 2014 - ICT for Energy Efficiency*, 723 (Oldenburg, 2014).

[3] M. Anvari, G. Lohmann, M. Reza Rahimi Tabar, M. Wächter, P. Milan, E. Lorenz, D. Heinemann, and Joachim Peinke, "Suppressing the non-Gaussian statistics of Renewable Power from Wind and Solar," (Submitted).

Measuring power output variability and unsteady loading in a micro wind farm model

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Key words: Wind farms, Interaction, Experimental, Unsteady loading, Porous disc

Very large wind farms, approximating the "infinite" asymptotic limit, are often studied with LES using periodic boundary conditions. In order to create an experimental realization of such large wind turbine arrays in a wind tunnel experiment including over 100 turbines, a very small-scale turbine model based on a 3cm diameter porous disk is designed. The porous disc matches a realistic thrust coefficient between 0.75-0.85, and the far wake flow characteristics of an operating wind turbine. Instrumented with a strain gage configuration and by making use of a model for the structural response, the porous disc model can be used to measure the thrust force, mean incoming velocity and representative power output. The frequency response of these measurements goes up to the natural frequency of the model and allows studying the spectra of the measured signals over a broad frequency range. This is shown by reproducing the -5/3 spectrum from the incoming flow.

LES studies have shown that there is a strong correlation between the power outputs of stream wise aligned turbines in large wind farms [2-3]. It is also found that the spectrum of the total power output follows a -5/3 power law [1,3]. However, based on a detailed analysis and comparisons with field data, the origins for this -5/3 power law and their connection with the wind farm layout and atmospheric boundary layer characteristics are not entirely obvious and still form an open question [1,3]. In addition to optimizing the wind farm layout for a maximum power output, we are also interested in unsteady loading of the wind turbines. For this purpose it is important to better understand the spatio-temporal correlations within the wind farm. In a first measurement campaign we make use of the high frequency measurement capabilities of the designed porous disc model to study the influence of row alignment on the power output variability and spatio – temporal correlations [4] for the power output and turbine loading. Figure 1 shows a conceptual rendering of the experimental setup.

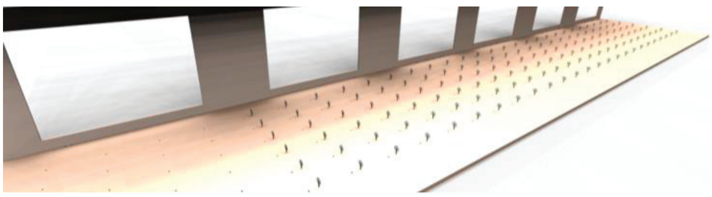

Figure 1: Conceptual rendering of a 'micro' wind farm in a wind tunnel

[1] J. Apt, "The spectrum of power from wind turbines", Journal of Power Sources **169**, 369-374 (2007).

[2] F. Porté-Agel, H. Lu, and Y. Wu, "Interaction between large wind farms and the atmospheric boundary layer", Procedia IUTAM 10, 307-318 (2014).

[3] R. J. A. M. Stevens and C. Meneveau, "Temporal structure of aggregate power fluctuations in large-eddy simulations of extended wind-farms", Journal of Renewable and Sustainable Energy **6**, 043102 (2014).

[4] M. Wilczek, R. J. A. M. Stevens, and C. Meneveau, "Spatio-temporal spectra in the logarithmic layer of wall turbulence: Large-eddy simulations and simple models", Journal of Fluid Mechanics, vol 769 (2015).

Wake effects in wind farms performances

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Key words: Wind farms, Wake Interaction, Large-Eddy Simulations

The increased demand for wind energy has led to continuous increase in the size of wind farms. However their efficiency is potentially inficiated by the effects of wake interactions. The use of simple wake models, although provides good estimate of overall performances when applied to single operating wind turbine, may furnish misleading results when applied to clustered configuration. The main reasons for this drawback is connected to the rather simplistic assumptions on the flow physics. On the other hand, Large-Eddy Simulation (LES) solvers, combined with the Actuator Line Model (ALM) to parametrise the wind turbine rotor, have shown to have the capabilities of representing detailed features of wind turbine wakes. However LES are characterised by a high computational cost.

LES of the flow past 3 aligned turbines varying the tip speed ratios ($TSR = \omega R/U_\infty$, where ω is the rotational speed of the rotor, R the rotor radius and U_∞ the freestream velocity) have been performed. Results are compared with those obtained with the Jensen-Park wake model. The entrainment of turbulent kinetic energy affects significantly the velocity impinging the turbines in the array. The entrainment is shown to depend on the *TSR* of the turbine. In fact, in Fig. 1(a) it is shown the streamwise velocity averaged over the rotor area obtained from LES at various *TSR*s of a single turbine with a laminar inflow profile: the wake recovery depends on the *TSR* and a change in the slope downstream the turbine is observed as the *TSR* increases. This behaviour is found to be even more evident when multiple aligned turbines are considered, see Fig. 1(b). Wake models are based on wakes' self-similarity and thus fail at predicting this behaviour. A comparison between ALM and Actuator Disk Model (ADM) for turbine modeling is also provided: in the present formulation the disk is rotating with a force distribution which depends on both the radial and azimuthal coordinate over the disk. With the ADM a smoother, though less detailed, field is obtained thus allowing a larger time step for the simulation.

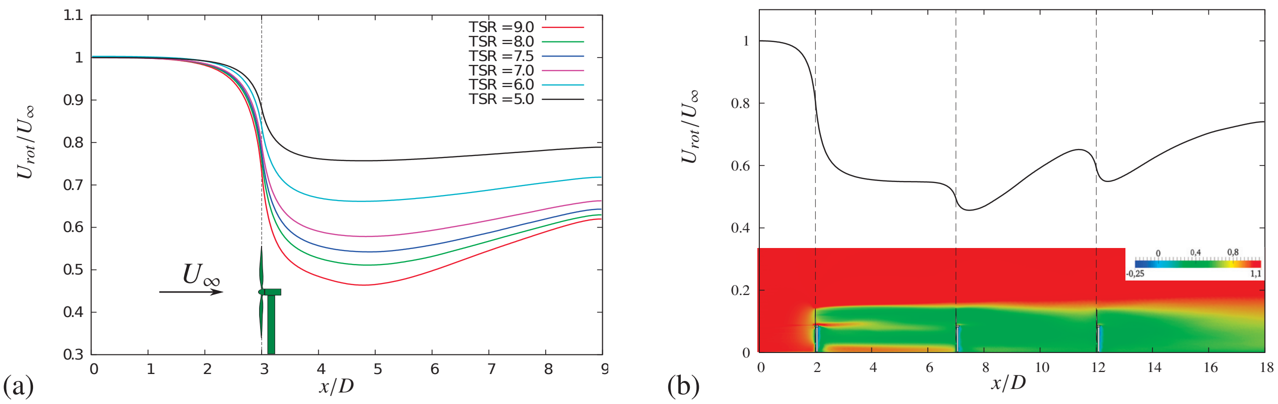

Figure 1: (a) Streamwise velocity averaged over the rotor area and (b) Streamwise velocity contours in the tower centreline vertical plane superimposed to rotor averaged velocity for a 3-turbine case: for each turbine $TSR = 7.5$

Electrical design of offshore wind power plants connected with VSC-HVDC trasnmission systems

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Key words: High voltage direct current (HVDC), Offshore Wind Power Plants (OWPPs), Variable frequency wind farm, Wake effects, Wind power generation

Offshore wind is a promising energy source which has attracted worldwide attention in recent years as a consequence of various circumstances, such as the lack of available onshore locations (mainly in Europe), the potentially higher and more constant wind speeds at sea than their onshore counterparts (enabling a greater wind power generation) and the fact that space limitations offshore are a less critical issue than inland, which allows the possibility of using larger wind turbines [1].

The trend of offshore wind power development is to built wind farms increasingly further from shore and in deeper waters by installing larger wind turbines. This fact is posing some technical, economic and political challenges that must be overcome to be fully competitive in the longer term compared to other energy sources. Today, there is an important concern about reducing the current Levelised Cost Of Energy (LCOE) of offshore wind projects by improving system reliability and availability, reducing O&M costs and/or increasing energy generation [2].

To this aim, this work proposes a different offshore wind power plant (OWPP) topology and presents a tool that allows to asses its cost-effectiveness in comparison with a conventional OWPP. This OWPP design is based on removing the individual power converters of each turbine and connecting a cluster of wind turbines or an entire OWPP to a single large power converter which operates at variable (SLPC-VF) taking advantage of HVDC technology and its ability to operate the wind farm collection grid out of synchronism with the onshore electrical network (50 or 60 Hz). The program takes into account both capital expenditures (CAPEX) and O&M costs over the lifetime of the OWPP. Wake effects among wind turbines and distributions of wind speeds and directions are considered in the study. To evaluate the suitability of the proposed OWPP topology, the model has been applied to a case study. The results suggest a good potential for the proposed topology achieving a costs savings of up to 5.18% in comparison to a conventional OWPP. The tool has been implemented in MATLAB using a Graphical User Interface (GUI).

[1] R. Berger, "Offshore wind toward 2020. on the pathway to cost competitiveness," Technical report, Roland Berger Strategy consultants GmbH, April 2013.

[2] "Levelized cost of electricity renewable energy technologies," Technical report, Fraunhofer ISE, November 2013.

Are your noise curtailment rules correctly applied? A case study involving automatic determination of operating modes through SCADA analysis.

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Key words: Wind turbine, Noise, Operating mode detection, Control, Performance

As the available space for siting wind turbines is becoming more and more limited, the erection of wind turbines occurs more and more frequently in challenging areas. In order to fulfill the environmental requirements for such places, limitations are imposed to wind turbines. One typical example is the noise restriction where the production of certain wind turbines has to be limited when the wind is blowing from specific wind directions in order to reduce the noise perceived by surrounding dwellings.

These rules have a major impact on the total energy and thus revenues produced by the wind farm. It is therefore very important to apply them properly in the turbine controller. . Unfortunately, although these rules are relatively simple – the wind turbine switching to a dedicated operating mode corresponding to specific environmental conditions (e.g., wind direction ranges, wind speed ranges, hour of the day, etc.) - it is very difficult to check the correct application of these rules. The first issue is related to the fact that usually no signal is provided by the turbine to notice the switch to a different operating mode. Therefore, the operating mode has to be inferred from a detailed analysis of the SCADA data.

This work presents an original method to automatically detect the current operating mode of a wind turbine based on a statistical analysis of the torque curve (torque versus active power). This detection also allows accurate performance measure metrics to be applied, taking the legal requirements into account.

The second issue is related to the reliability of the wind direction measurement. Indeed, any offset on this channel directly leads to an incorrect application of the curtailment rules. A method using change point analysis in order to automatically detect change in nacelle wind vane offset will be presented.

These analyses will be presented using a case study where an incorrect application of curtailment rules has been detected using the above mentioned techniques will be presented. Such detection can lead to reduced risks of fines and increased performance for operators, as well as the appropriate application of performance metrics under such conditions.

Data-driven RANS simulations of wind turbine wakes

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Key words: Data assimilation, RANS, wind turbine wakes

Efficient and less costly numerical tools are highly sought for wind energy research and industry in order to design large wind power plants, optimize power harvesting, monitor and control wind turbines. The highest level of accuracy for prediction of wind turbine wakes and performance is typically achievable via Large Eddy Simulations (LES), which mimic wind turbine forcing on the atmospheric boundary layer through actuator line or actuator disc models [1]. Although very accurate results are obtained through LES, the high computational costs required make them inapplicable for large wind farm cases, investigations of large sets of operational conditions (e.g. wind direction, tip speed ratio), and for real-time applications. RANS codes have been also applied for simulations of wind turbine wakes, but resulting in a limited accuracy connected to the tuning of the turbulence closure models [2]. For the above-mentioned reasons, simple analytical wake models are still broadly used for design and optimization of wind farms.

In this work the wake flow and power performance of very large wind farms are simulated through a RANS approach, where the closure turbulence model is calibrated with a data-driven procedure. The turbulence model is formulated through the Boussinesq hypothesis, and the eddy viscosity is evaluated via generalized mixing length model [3]. Specifically, the mixing length is evaluated from data provided from a wake monitoring system, which for real applications can be represented by a scanning Doppler wind LiDAR. Specifically, the mixing length is obtained through a fitting procedure between the radial shear of the axial velocity and the Reynolds stress between the axial and radial velocities.

In this work high fidelity LES simulations of a utility-scale wind turbine operating at different loading conditions are used as database for the tuning of the RANS turbulence closure model. The mixing length is found to vary linearly with the downstream location and its slope increases with higher tip speed ratio. Therefore, wind turbine wakes operating with a higher load are characterized by a faster wake recovery rate. Data-driven RANS simulations are performed by providing as initial condition the wake velocity profile at a certain downstream location obtained through the LES simulations. The simulations through the data-driven RANS of the downstream evolution of the wake flow is in good agreement with the LES data. These results assess the potential of the proposed methodology for fast simulations of large wind farms, real-time predictions of operative conditions, and wind farm control. (This work is partially founded by the National Science Foundation, grant number IIA-1243482, the WINDINSPIRE project).

[1] L. A. Martinez-Tossas, M. J. Churchfield and S. Leonardi, “Large eddy simulations of the flow past wind turbines: actuator line and disk modeling," Wind Energy (2014).

[2] J. F. Ainslie, “Calculating the flowfield in the wake of wind turbines," J. Wind Eng. Ind. Aerodyn **27**, 213-224 (1988).

[3] S. B. Pope, *Turbulent flows* (Cambridge University Press, Cambridge, 2000).

Turbulence inflow generation for a turbulent boundary layer over rough hills under neutral and stable conditions

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Key words: Synthetic turbulence inflow, hill flow, atmospheric stability

Most of existing large wind farms are located in flat terrain which has good wind resources and is easy to access [1]. However, such terrains become scarce in the developed wind market, and thus it is necessary to explore wind farm sites in complex terrain. Therefore, it is important to investigate what the current challenges and uncertainties are in designing wind farms in complex terrain.

To date, popular wind farm design tools for wind resource assessment are not generally able to represent complicated phenomena frequent in complex terrain. This is because difficulties in defining boundary conditions [2], and representing atmospheric stability [3]. Therefore, the objectives of this study are; To assess an existing turbulence inflow generation method on turbulent boundary layer over rough hills, and to demonstrate the ability of the suggested numerical approach to represent atmospheric stability.

Computational fluid dynamics (CFD) with eddy-resolving hybrid RANS-LES turbulence model was used for the present study. The finite volume solver FLOWer [4] was adopted as a flow solver. It is noted that turbulence inflow generation (see Fig. 1) and rough wall modelling were implemented recently in FLOWer, which are necessary for the present study. Details of numerical descriptions and statistical data will be presented in the conference.

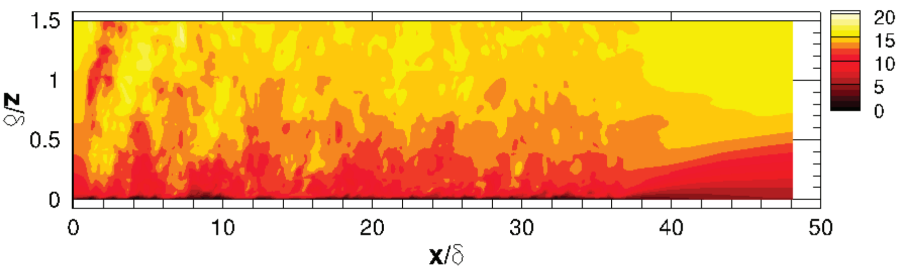

Figure 1: Instantaneous velocity field u^+ for a rough wall boundary layer. A synthetically generated 3D turbulence field was introduced at $x/\delta = 1$ by a momentum source term, where δ is the boundary layer thickness. A cell stretching was applied for $x/\delta > 36$.

[1] P.W. Cheng, Th. Lutz, A. Rettenmeier and M. Hofsäß M, “Introduction Note: Wind energy development in complex terrain”, IEA R&D Wind Task 11 - Topical Expert Meeting: Challenges on Wind Energy Deployment in complex Terrain, (2013).

[2] A. Bechmann, N.N. Sørensen, J. Berg, J. Mann and P.E. Réthoré, “The Bolund experiment, Part II: Blind comparison of microscale flow models", Boundary-layer Meteor. **141**, 245-271 (2011).

[3] J. Bleeg, D. Digraskar, J. Woodcock and J.F. Corbett, “Modeling stable thermal stratification and its impact on wind flow over topography", Wind Energy. **10.1002/we.1692** (2014).

[4] N. Kroll, C.C. Rossow, K. Becker and F. Thiele, “The MEGAFLOW project", Aerosp. Sci. Technol. **4**, 223-237 (2000).

Estimating instantaneous and cumulative loads in wind turbines through a simple stochastic method

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Key words: Fatigue Loads, Loads estimation, Stochastic method, Wind farms

We describe a stochastic method which provide accurate estimates of turbine loads only recurring to standard measurements, such as anemometer wind velocity, without using direct load measurements. The data analyzed was taken at Senvion's Alpha Ventus (AV) wind turbines, namely at AV4 and AV5, from 2012 to 2014, and is part of the project "Probabilistic loads description, monitoring, and reduction for the next generation offshore wind turbines (OWEA Loads)", funded by the German Federal Ministry for Economic Affairs and Energy. We analyze available loads at AV4 for deriving our model: the torque, the bending moments and acceleration measured at the blades and at the tower, taken at sample frequency of 50 Hz.

Our approach has two main steps. First, we extract an evolving equation[1] which yields a stochastic differential equation, which, combined with wind velocity measures is able to reproduce statistically the series of load measurements at wind turbine AV4. Second, the model derived from the measurements taken at AV4 are then applied to reconstruct each instantaneous and cumulative load at AV5 and compare them to the corresponding set of measurements. Previous studies have shown a successful estimation of torque series[1] and fatigue loads[2] in AV wind turbines.

With this proposed approach it should become possible to efficiently estimate the loads of all wind turbines in a wind farm and, additionally, the individual working conditions for the turbine in wake or multiwake can be grasped, too.

[1] P. G. Lind, M. Wächter and J. Peinke, "Reconstructing the intermittent dynamics of the torque in wind turbines", Journal of Physics: Conf. Ser. **524**, 012179 (2014).

[2] P. G. Lind, I. Herráez, M. Wächter and J. Peinke, "Fatigue Loads Estimation Through a Simple Stochastic Model", Energies **7**, 8279-8293 (2014).

A Linear State-Space Model of an Offshore Wind Power Plant

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Key words: linear, state space, control

Models are needed in order to understand the dynamics of large offshore wind power plants, from the atmosphere to the seabed, and the generator to the point of common coupling with the onshore grid. Tools originating from individual disciplines, like aeroelastics or electrical grids, tend to contain highly simplied representations of other disciplines. Integrated models are needed, both as a check on the discipline-specific simplifications, and as a means to quantify the impact of various design decisions on the system as a whole.

Linear models, where applicable, provide a means to rapidly understand the dynamics of a system. In particular, the principle of superposition allows a problem to be broken into individual pieces, and subsequently assembled into the total response. Cause and effect can be explicitly identified; this often takes the form of spikes in the frequency transfer function between two quantities of interest. The stability properties of the system can be computed explicitly, as can optimal gains for the control systems.

Our hypothesis, based in part on initial investigations on the aeroelastic behavior of wind turbines [1], is that the stochastic response of an offshore wind power plant under normal operating conditions (10% turbulence intensity) can be reasonably represented by a linear model. This includes most of the relevant outputs: internal loads in the structure, current and voltage levels in the electric grid, and fluctuations in the windspeed. This latter claim, that the wind behaves linearly, seems tenuous; but the development of the atmospheric boundary layer through a wind power plant is well-modelled by linearizations of the Navier-Stokes equations [2], and the global effects of rotor pitch-control perturbations could be modelled using similar methods.

We are presently building a unified linear state-space model of a wind power plant that will be used to test the hypothesis of linearity, and to assist in developing control algorithms. The latest results will be presented at the colloquium.

[1] Merz KO, "Rapid optimization of stall-regulated wind turbine blades using a frequency-domain method: Part 1, loads analysis," Wind Energy (2014), DOI: 10.1002/we.1786

[2] Frandsen ST *et al.*, "The making of a second-generation wind farm efficiency model complex," Wind Energy **12** (2009) 445-458, DOI: 10.1002/we.351

Empirical analysis of wake effects in an operating wind farm

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Key words: Wake effects, empirical, wind farm

Wake effects do not only affect the power production of wind turbines, but have also an important influence on, among others, the fatigue life consumption of wind turbines[1]. Therefore it is important to gain insight into the wake flows through a wind farm, not only by simulations but also by developing empirical models based on data of an operational windfarm. This contribution will summarise a first analysis regarding wake effects observed at the Northwind offshore windfarm outside the Belgian Coast.

A first step towards better understanding of the wake effects within a wind farm is taken by analysing a subset of the turbine SCADA for the full farm. This analysis will show how parameters like averaged windspeed, power production and turbulence intensity vary within a wind farm, dependent of the wind direction. We will also show the variation in power production for a row of turbines standing in the wake of each other, for several ranges of windspeed.

Further analysis of wake effects will lead to a better understanding of the behavior of several parameters, e.g. power production. Eventually, this analysis will allow to develop an empirical model for the wake effects within a windfarm and compare different lay-outs of windfarms to each other.

[1] "Monitoring the consumed fatigue life of wind turbines on monopile foundations", Wout Weijtjens, et al., EWEA Offshore 2015 Copenhagen

Design of closed loop control for a wind turbine system coupled to a CV transmission system.

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Key words: Wind turbine control, Continuously variable transmissions, Grid Integration, DFIG.

Grid integration of renewable energy sources has proven to be a popular and challenging problem that has been extensively studied and continues to be a focus of interest. Most modern wind energy conversion systems utilize power electronics converters/inverters to maintain voltage phase, frequency and magnitude at the grid-dictated values.

While power electronics is an expanding area of interest, currently available solutions report high failure rates and elevated monetary costs. In this paper we investigate the dynamic analysis of a gearless wind turbine coupled to an induction generator based on the dynamic understanding proposed *by Ericson and Srivastava* that describe both the steady state and the shifting behaviors of the V belt CVT. The Model uses the dynamics published by Carbone-Mangialardi to explain this relationship during creep mode shifting, and the dynamics by Shafai in Slip Mode shift, which provides thorough detail on the inertial interactions between the belt and the pulleys of CVT.

Using Matlab/Simulink, we incorporate the CVT model into a wind turbine model coupled to an induction generator. The entire turbine/rotor – CVT/generator is coupled to the grid through the conventional grid- and rotor- side converters. By controlling the driver axial forces of the CVT we control low- and high- speed shaft speeds (i.e. perform speed control) to obtain maximum wind energy capture before the wind cut-out speed and provide an alternative to pitch control afterward.

The intent is to show how control inputs of the CVT affect power through the entire drivetrain to meet the objectives of:

a) Maximal power extraction from the wind
b) Better quality power for grid integration
c) Tracking the grid demands without degrading the CVT performance

The results for the overall integrated powertrain are presented and discussed in detail with the CVT and the induction generator operated in ***closed loop*** configuration. The simulations were all performed utilizing real wind data taken from a met tower in the South plains area, the data was sampled at 50 Hz.

The correct control of a gearless wind turbine yields encouraging results such as:

- Improve energy capture (wider speed range).
- Downsize of pitch control.
- Downsize, if not completely eliminate, speed control needed on HSS and/or LSS. Traditionally, speed control on LSS and HSS is done by RSC (Significant reduction of power electronics, 25% of failures in wind energy industry is due to power electronics).
- Reduce switching electronics needed to ensure a constant grid frequency of 60 Hz.

Fluid-structure interaction of a wind turbine blade employing a refined finite element model coupled with a blade-element momentum method

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Key words: Wind turbine blades, Fluid-structure Interaction

Typically the aero-elastic simulation tools that are used in industry employ simple beam models to represent the blades of a wind turbine. The aerodynamic loads are usually calculated using a fast blade-element momentum (BEM) method. These models allow relatively fast calculation of the aero-elastic behavior of the blade which is required in order to allow the simulation of a large number of load cases as required by the IEC 61400 [1] and GL [2] standards in a feasible amount of time. Such beam models do however not incorporate the level of detail required to provide the complete stress and strain distribution in the blade, nor are they able to take into account nonlinear effects such as the change in cross-section of the blade due to the brazier effect [3]. Alternatively, highly detailed 3d computational fluid dynamics (CFD) simulations can be coupled with refined finite element (FE) models to obtain highly accurate results both regarding the flow around the blade as regarding the stress and strain distribution within the structure. However, the computational cost of such a simulation is enormous.

In this work a coupling has been developed between the BEM code HAWC2-aero, which was developed by DTU [4] and the Abaqus FE solver. This allows a fluid-structure interaction (FSI) simulation by means of a so-called "weak" coupling, meaning that the two different solvers are run sequentially in iterations until convergence is achieved. In this way, a refined structural model is coupled with a fast aerodynamics tool, allowing steady-state fluid-structure interaction (FSI) simulations at an acceptable computational cost.

The more advanced structural model allows the investigation of the influence of structural properties such as individual composite plies as well as their positioning, orientation and materials on the aero-elastic behavior of the blade. The influence of non-linear effects on the blade's aero-elastic behavior can also be analyzed.
The finite element model is used to locate stress hot-spots or buckling effects. Loads were applied using two different methods. One method uses distributing couplings to spread the load of a spanwise cross-section over all the nodes on that section. The other method uses concentrated forces at specific nodes to introduce the loads.

[1] International Electrotechnical Commision. International standard. Wind turbine generators. IEC 61400; 2006.
[2] Germanischer Lloyd: Rules and guidelines industrial services IV – guideline for the certification of wind turbines, Edition 2010; 2010.
[3] Brazier, L.G., On the Flexure of Thin Cylindrical Shells and Other "Thin" Sections. Vol. 116. 1927. 104-114.
[4] Larsen, T.J., HAWC2aero, the user's manual. 2008, Risø National Laboratory: Roskilde, Denmark.

Conditional sampling of wind farm flow fields

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Key words: Wind farms, Conditional averaging, Multibody dynamics, LES

In large wind farms the turbines are heavily loaded by the turbulent wakes of the upstream rotors. These loads can lead to severe damage of the wind turbine components. In order to improve turbine control, further insight into flow patterns that cause these structural loads is of interest.

In the current work conditional averaging is used to examine the effect of turbulent flows on the turbine loads. Conditional sampling has been used with success for the identification of large-scale turbulent structures in various experimental studies, e.g. Refs [1, 2]. Here, we apply this method to numerical simulations of wind farms using structural dynamics variables as conditions for the average. In this way the flow field is averaged for every realization of a trigger condition, shedding light onto the interdependence between flow patterns and structural response.

The simulations are performed using our in-house large-eddy simulations code SP-Wind [3], which utilizes a highly-parallelized pseudo-spectral spatial discretization scheme and a fourth-order time-marching scheme. To account for the tower and blades dynamics, a flexible multibody dynamics code has been implemented and integrated into the SP-Wind code. The multibody dynamics module employs the floating frame of reference formulation [4], and the model order is further reduced using modal transformation.

Results are shown for aligned wind farm layouts operating at rated or above-rated flow regimes in neutral atmospheric boundary layer conditions. These include mean flow field variables and turbulence properties correlated with different trigger conditions for blades displacement and power output.

[1] C. W. Van Atta, "Sampling techniques in turbulence measurements," Ann. Rev. Fluid Mech. **6**, 75-91 (1974).

[2] R. A. Antonia, "Conditional sampling in turbulence measurement," Ann. Rev. Fluid Mech. **13**, 131-56 (1981).

[3] M. Calaf, C. Meneveau and J. Meyers "Large eddy simulation study of fully developed wind-turbine array boundary layers," Physics of Fluids **22**, art. no 015110 (2010).

[4] A. A Shabana, *Dynamics of Multibody Systems, Fourth Edition* (Cambridge University Press, New York, 2013).

Fatigue assessment of an operational offshore windfarm

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Key words: Monitoring, Fatigue life, Turbulence

Fatigue life is a design driver for the foundations of offshore windfarms. This contribution will present the results of an ongoing monitoring campaign at the Northwind offshore windfarm outside the Belgian Coast. The monitoring campaign is set up to monitor the progression of fatigue life throughout the operational life of the farm.

In this contribution we will focus on how fatigue life is affected for an operational turbine using strain measurements on two operational turbines, a subset of the turbine SCADA and the meteorological conditions at the site. These measurements will provide important insights in what are true drivers behind fatigue. We will also look into more detail how the interaction between turbines affects the fatigue life of an individual turbine. It will be shown how accelerated fatigue life consumption is observed for wind directions in which a turbine is receiving turbulent air. This behavior is illustrated in Figure 1.

The interaction between environmental conditions and fatigue life consumption has a direct effect on how fatigue life progresses within a farm and will ultimately result in turbines that age quicker than others. A proper understanding of these dynamics behind fatigue will in long-term allow to develop a model for farm-wide fatigue assessment for decision support at end-of-life and for O&M.

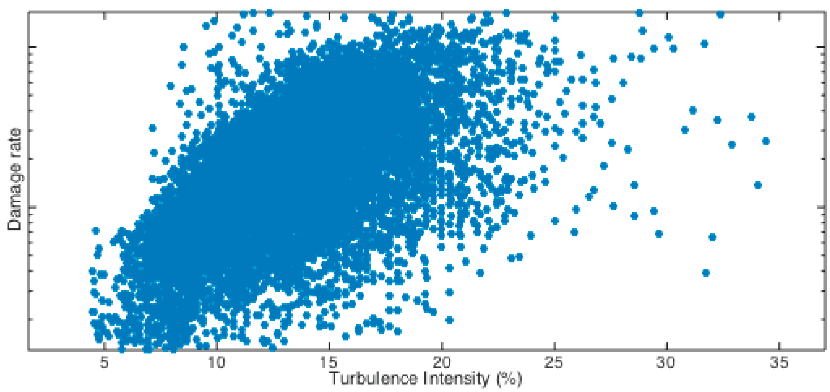

Figure 1: Measurements reveal a relation between the fatigue life consumption rates and the turbulence intensity